SEMANTIC CLUSTERING MECHANISMS FOR COMMUNICATION IN WIRELESS SENSOR NETWORKS

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I dedicate this thesis to my beloved parents.

Abstract

In the past few years, advances in wireless technology and energy efficient devices have enabled a new kind of wireless networks called wireless sensor networks. Applications using these networks span a wide range, including patient health monitoring, environment observation, and building intrusion surveillance. However, these networks suffer from resource constraints that do not appear in more traditional wire networks. In particular, nodes are battery-operated, often limiting available energy, and wireless spectrum is scarce, often limiting the bandwidth available to applications. Therefore, there is a real need to design communication techniques that could minimize the amount and range of communication as much as possible, in order to prolong the life time of the sensor network. To tackle these resources constraints and adapt to the harsh environment new communication protocols need to be designed rather than the traditional layered approach protocols and new techniques like clustering and data aggregation need to be implemented. At the other hand, users of wireless sensor networks are, usually, interested in monitoring physical events that occur in the monitored environment. Therefore, besides the resource constraints imposed by the network, routing protocols need to respect the user interest and consider the semantic properties provided by each node in the network.

This dissertation addresses these issues by proposing semantic clustering mechanisms for communication in wireless sensor networks. The proposed mechanisms are composed of four novel communication schemes: a semantic clustering routing protocol, an energy efficient routing clustering for mobile event monitoring, a node recovery scheme for data dissemination, and coordination framework for single actor model in wireless sensor and actor networks.

Our new semantic clustering protocol allows to group sensor nodes in a cluster according to their relevancy to user queries and data interest. Nodes inside the same cluster are organized like a tree where the cluster-head is the root. This semantic clustering protocol allows a layered data aggregation, avoids the cluster head overload and offers more energy saving, while satisfying the user query.

In the area of mobile events monitoring we proposed a new clustering protocol that allows gathering information about a mobile event in an energy efficient way. In this protocol sensor nodes within the event area are, firstly, grouped in a cluster with a tree organization where the nearest sensor node to the event source is the root of the tree and the cluster head at the same time. The cluster is maintained, when the observed event is moving, using a cluster membership update scheme, that allows sensor nodes to join or leave the cluster, and cluster head re-election, according to their sensed signal. Moreover, as event may split in two or more new sub-events, we proposed a cluster split scheme that allows the user to monitor the event split and the resulting new events.

Our third contribution is a node recovery scheme that maintains a single data dissemination path between sensor nodes and the user, by replacing energy exhausted nodes by new neighbouring nodes. The proposed recovery scheme exploits the network density and the broadcasting nature of the wireless medium to replace the energy depleted nodes in the communication path, and thus maintains the network connectivity and extends its lifetime.

In the area of wireless sensor and actor networks we proposed a coordination framework for the single actor model. In this framework, the network is organized initially in a Voronoi diagram, in which each Voronoi region contains an actor and its nearest sensor nodes. We used our semantic clustering protocol to group nodes detecting the same event in a cluster, and the nearest node to the event source is elected as cluster head. Nodes within the cluster are organized in form of tree, where the cluster head is the root. The role of the cluster head in this framework is to inform the nearest actor to event source about the detected event.

We have analyzed the proposed protocols and schemes and evaluated their performances using analytical study and simulations. The evaluation was based on the most important metrics in wireless sensor networks, such as: energy consumption and time delay. The evaluation shows that our mechanisms achieve efficient energy consumption, good data quality and acceptable time delay. A comparison with existing communication protocols reveals that our solution is more energy efficient, extends the network lifetime much longer, and provides more accurate data to the user.

Table of Contents

List of Tables

List of Figures

1 Introduction

Wireless sensor networks are a promising technology for applications ranging from environmental monitoring to industrial asset management [Akyilidz'02]. This type of networks is expected to change our life in many ways, in schools, hospitals, houses, and many other places. In health, for example, sensor networks may be used to monitor the patient health state, by deploying many small sensor nodes in different parts of his body. Sensor networks can be used in other scientific study applications, like habitat monitoring, environment observation, and home or office applications [Biagioni'02, Biagioni'03, Cerpa'01].

Wireless sensor networks are, generally, formed of tiny, low-power, low-cost, multifunctional, sensor nodes that could be mobile and may be deployed in unfamiliar environments. These tiny sensor nodes consist of sensing, data processing and communicating components, and communicate untethered over short distances. Each sensor node obtains a certain view of the environment. As a sensor node has limited sensing range and low power processing CPU, the obtained view of the environment is usually limited in both range and accuracy; it can only cover a limited physical area of the environment. However, by combining the views retrieved from the individual sensor nodes, the users can accurately and reliably monitor the studied environment. In order to enable remote monitoring of an environment, the sensor nodes must send their readings to a distant base station called generally the sink, through which the user can access to the collected data, as it is illustrated in figure 1-1.

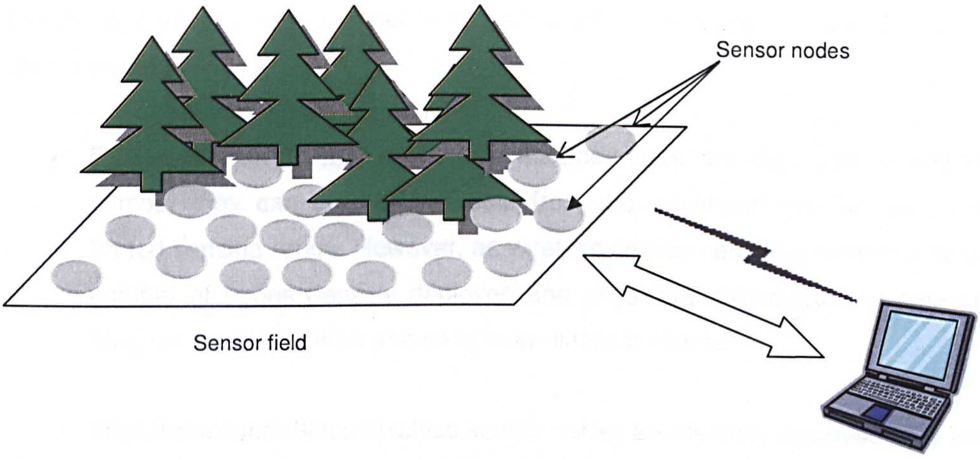


Figure 1-1: An example of a wireless sensor network

Wireless sensor networks represent a new paradigm for retrieving data from the environment. Conventional systems use large, expensive macrosensors that are usually wired directly to the end user base station and need to be accurately deployed to obtain the required data. For instance, in tomography large arrays of geophone sensors attached to huge cables are used to determine the internal structure of the Earth. This technique, used mainly by oil companies, is very costly if we know that such sensors are very expensive and their deployment requires lot of efforts [Schuster'99]. Since the number of sensors is very limited they need to be placed in exact locations in order to retrieve accurate information, and then reallocate them afterwards to another area. Such operation requires very expensive tools such as helicopters to transport the system and bulldozers to ensure the sensors are placed in exact positions.

Therefore, the replacement of such bulky and expensive macrosensors by hundreds of cheap microsensors that can be deployed easily would represent a large economic and environmental gain. These microsensors would be fault tolerant and deployed with sheer number which ensure redundancy in data acquisition and better coverage of the environment. Furthermore, since these networks use wireless medium for communication, the need for a fixed infrastructure would be eliminated.

The deployment of a huge number of sensor nodes brings many new benefits to the user, including:

- **Extended monitoring range**: As macrosensors are deployed in limited number they can only extract data from the monitored environment with limited sensing range. However, as wireless sensor networks contain a large number of nodes densely deployed and physically separated; the sensing range is more extended and can cover different events.

- **Fault-tolerance**: Since wireless sensor nodes are densely deployed they are located near to each other which makes these systems much more fault tolerant than traditional macrosensors systems.

- **Accuracy**: While a single wireless sensor node's data might be less accurate than a macrosensor' data, combining the data from different wireless sensor nodes increases the accuracy of the sensed data.

- **Lower cost**: Even thought wireless sensor nodes need to be deployed in huge number to ensure reliability, fault tolerance and accuracy, they still represent a cheaper solution comparing to macrosensors.

Wireless sensor networks enable the reliable monitoring of a variety of environments for applications like habitat monitoring, home security, chemical attacks detection, medical monitoring, and surveillance.

Moreover, by adding more powerful, highly mobile and sparsely deployed actor nodes, it becomes possible to take autonomous decisions without the user intervention. These networks will help to react quickly to certain events that happen in the environment. This networks are usually called wireless sensor and actor networks [Akyilidz'04]. Wireless sensor and actor networks are capable of observing the physical world, processing the data, making decisions based on the observations and performing appropriate actions. These networks can be an integral part of systems such as battlefield surveillance and microclimate control in buildings, nuclear, biological and chemical attack detection, home automation and environmental monitoring. For example, if a wireless sensor and actor network is deployed in a forest to detect a fire, sensors relay the exact origin and intensity of the fire to extinguisher actors so that the fire can easily be extinguished before it becomes uncontrollable, as it is illustrated in figure 1-2. Similarly, motion and light sensors in a room can detect the presence of people and then command the appropriate actors to execute actions based on the pre-specified user preferences.

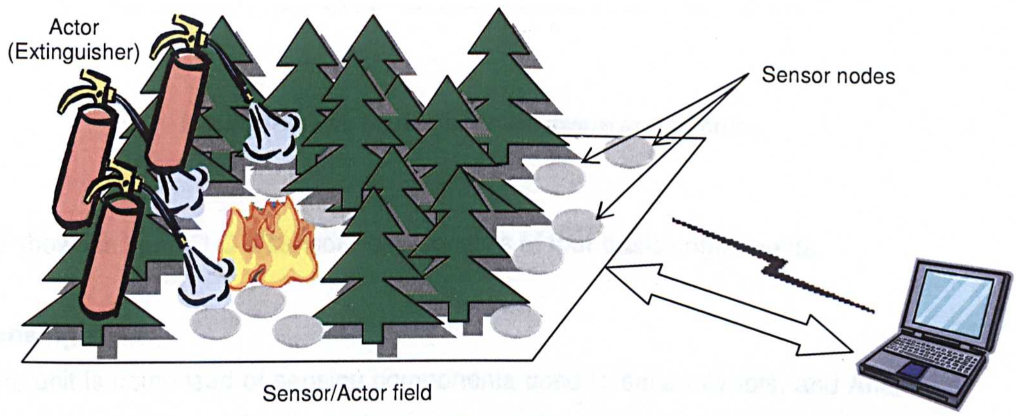


Figure 1-2: An example of a wireless sensor and actor network

1.1 Wireless Sensor Nodes Hardware

A sensor is a device that maps a physical quantity from the environment to a quantitative measurement. In the past few years, micro-electro-mechanical systems (MEMS) technology has known an important progress promising to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. This technology has enabled the development of small, relatively inexpensive and low power sensor nodes.

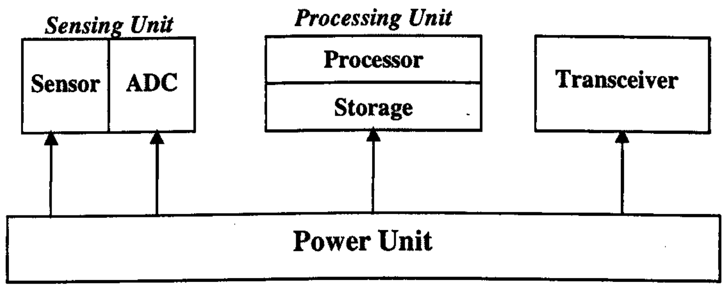


Figure 1-3: The sensor node hardware architecture

As shown in figure 1-3 a sensor node consists of four basic components:

Sensing Unit:

This unit is composed of sensing components used to sense events, and Analog to Digital Converters (ADCs) which convert analog signals, produced by sensors based on the observed phenomenon, to digital signals.

Processing Unit:

The main task of this unit is the management of data processing procedures that allow the sensor node collaboration with other nodes. This unit is generally associated with a small storage unit. Although the higher computational powers are being made available in smaller and smaller processors, processing and memory units of sensor nodes are considered as limited resources comparing to the volume of data generated by the sensors.

Transceiver Unit:

This unit connects the node to the network. Transceiver may be an optical device that uses light propagating in free space to transmit and receive data. However, the main drawback of this technology is its limitation under certain climatic conditions such as fog, rain, snow, etc. As the sensor networks have low data rate, small data packets, and use short communication distances, the radio frequency (RF) communication is preferred in most sensor network research projects [Cheek'05, Vieira'03].

Power Unit:

In a sensor node, power unit is one of the most important components because the lifetime of a sensor network depends on the lifetime of the sensor nodes battery. For example, battery used in Smart Dust prototype allows sending 5.52 million messages. It is possible to extend the lifetime of the sensor networks by energy scavenging, which means extracting energy from the environment using solar cells.

1.2 Wireless Sensor Networks Characteristics

The sensor nodes are very small in size, low powered and have limited memory, and are typically deployed densely in small or medium area. These factors add new constraints to wireless sensor networks not found in traditional networks.

First, wireless sensor networks suffer from resource constraints that do not appear in more traditional networks. In particular, nodes are battery-operated, with limited available energy. In the situation where wireless sensor networks are deployed in remote or dangerous territory, it may be impossible to recharge sensor nodes batteries. In other applications like medical monitoring or machine monitoring, it may be inconvenient to replace the batteries of sensor nodes.

Second, sensor nodes are deployed densely in the study field; the number of nodes deployed may be in order of hundreds or thousands and may be millions depending on the application. This dense deployment results in huge amount of highly correlated sensor observations in the space and time domains. The important amount of data generated by sensor nodes makes the communication spectrum scarce and limits the bandwidth available to applications.

Third, due to the sheer number of sensor nodes deployed, it is not feasible to assign addresses to each node as it is the case in traditional networks. This lack of global identification along with random deployment of sensor nodes makes it hard to select a specific set of sensor nodes to be queried. Therefore, nodes must be selected according to their physical observations.

1.3 General Requirements for Wireless Sensor Networks

Wireless sensor networks are expected to be easily deployable and possibly in remote dangerous environment. Therefore, it is important that the sensor nodes are able to communicate with each other even in the absence of an established network infrastructure. In addition, there are no guarantees about the locations of the sensors, as they are generally randomly deployed. Hence, wireless sensor nodes need to be self-configuring and require no global control to set-up or maintain the network. Moreover, since sensor nodes are energy limited, the wireless sensor network should be considered as having a certain lifetime during which sensor nodes can collect, process, and transmit data to the user. Therefore, all the aspects of the node, from the sensor module to the hardware and protocols, must be designed to be extremely energy-efficient. Decreasing the energy dissipation by a factor or two can extend the network lifetime to a double.

In addition to the requirements related to the sensor nodes, it is also important to consider the applications and the users' needs as well. The more important application-related parameter that needs to be considered in wireless sensor networks is the data quality. This parameter measures the accuracy with which the result of the sensor network matches what is actually occurring in the environment. However, this parameter is an application-specific parameter and depends heavily on the application profile.

Latency is another application-specific parameter that needs to be considered in wireless sensor networks. Indeed, wireless sensor networks applications are typically time-sensitive, so it is important to receive the data in a timely manner. Long delays due to processing or communication may be unacceptable.

However, tradeoffs can be made among these different parameters, and protocols should be scalable and adaptive to change according to the importance of the different parameters. For example, when energy is sufficient, the user may desire high-accuracy results. As the energy gets depleted, the user may request that the accuracy of the results be reduced in order to reduce the energy dissipation in the nodes and hence extend the network lifetime.

Researcher have been studying wireless networks for a number of years and have developed fairly sophisticated protocols for voice delivery using cellular networks and data delivery over wireless local area networks and ad-hoc networks [Broch'98, Garg'95, Pahlavan'95]. In cellular networks, nodes are organized into clusters where each node is able to communicate directly with the cluster base station. Such networks require a fixed infrastructure so that nodes can be connected to the network wherever they are. Wireless local area networks usually require point-to-point connectivity so any user can communicate with any other user, often without the use of a central base-station; for that these networks typically use multi-hop routing protocols. While these protocols are suitable for optimizing delay and fairness parameters, they are designed for applications where each user is creating data that may be transferred to any other user at any given time. These goals are completely different from wireless sensor networks goals. Indeed, in a wireless sensor network data sensed by each node are required at a remote base station, rather than other nodes. Also the raw data extracted from the environment by the sheer number of sensor nodes leads to large amounts of redundant data. However, the wireless sensor networks users do not require all collected data to be sent to the sink, for two main reasons:

- First, the user, usually, cares about a higher-level description of event occurring in the monitored environment.

- Second, the data collected, in the area where the described event has been detected is, usually, highly correlated.

Therefore, the quality of the result is based on the quality of the aggregated data rather than the quality of individual sensor node reading. Thus, protocols should be designed to be more application specific and optimize the applications required quality while minimizing the resources consumption. This means that wireless sensor networks protocols should be designed to satisfy the following conditions:

➢ Self-configuration to enable ease of deployment of the networks.

➢ Energy-efficiency and robustness to extend the network lifetime.

> Consideration of the semantic properties of the retrieved data, the application profile, and user requirements.

1.4 Problem Definition

Communication architectures and routing protocols are major challenges in wireless sensor networks. Wireless communication is the major source of energy consumption. Thus, new protocols are needed to minimize the number of packets to be sent to the sink.

At the other hand, users of wireless sensor networks are generally interested in gathering information about a specific event or phenomenon that occurs in the physical environment. However, as described before, since wireless sensor nodes are densely deployed, it is more likely that many nodes will be in the described event area, and thus satisfy the user interest. Consequently, the sensor nodes response to the user interest may result in a huge amount of redundant data. Knowing the resources constraints that characterize wireless sensor networks, the challenge is to design a new routing protocol capable of reducing this data amount as much as possible while providing highly described information to the user.

Moreover, wireless sensor networks use multihop communication, and since sensor nodes are energy limited and prone to failure, these networks need a robust data dissemination approach that guarantee the data delivery of the gathered data to the user. Therefore, it is important to propose a robust data dissemination approach that ensures a reliable delivery of the collected information to the user at minimum costs.

In addition, in many wireless sensor networks applications, users might be interested in gathering information about certain mobile physical phenomena, and want the sensor nodes to retrieve information continuously about the monitored event while it is moving. The challenge is to design a new routing protocol that can collect and deliver information about mobile events to the user in an energy efficient way.

The user is not the unique destination of the data gathered by sensor nodes. In wireless sensor and actor networks, sensor nodes gather data about a specific event and send it to actor nodes to perform a specific action. However, since sensor nodes operate independently from any central control unit, any event that occurs in the study field generates a huge number of data messages sent to many actors, which may result in overlapping of their actions. Therefore, in addition to resources constraints, data accuracy and mobility, coordination between sensor and actor nodes is also a necessity in the design of routing protocols in wireless sensor networks.

1.5 Research Objectives

The goal of this research is to design data dissemination and routing protocols that satisfy wireless sensor networks requirements. These protocols must extend the network lifetime; provide reliable data delivery and high level information to the user.

This goal will be achieved via the following detailed objectives:

1. To design a new routing approach that can help to deliver the information required by the user while reducing the amount of data sent and save scarce resources. This approach can be evaluated by comparing it to existing approaches and show how much energy saving it achieves.

2. To design a node recovery scheme that makes the data dissemination more robust and extends the network connectivity lifetime. This node recovery scheme will be able to recover energy exhausted and replace them with their neighbouring sensor nodes. This recovery scheme will be associated with a simple single path data dissemination protocol and will be compared with existing data dissemination approaches to show its effectiveness and reliability.

3. To design an energy efficient routing protocol for mobile event monitoring applications. This protocol will take into consideration the features of monitored event such as, the event nature, the event speed, event split etc, while achieving accuracy and energy efficiency. We will analyze the lifetime

extension achieved using this protocol and compare it to other existing approaches.

4. To design a coordination framework for the single actor model in wireless sensor and actor networks based. This framework will group nodes within a certain area of event in order to call a single actor to deal with the event. Thus, it avoids unnecessary data messages. To evaluate this work we can verify if the framework satisfies the single actor model condition and what are the cost of such procedure in terms of energy consumption and time delay. This can be carried out through simulations.

1.6 Novel Research Contributions

In this thesis, we present new communication mechanisms for wireless sensor networks based on semantic clustering. We have proposed novel communication solution that consists of new routing algorithms and mechanisms in order to address the emphasized challenges and achieve our research objectives. Our contributions can be summarized as follows:

- **A Semantic Clustering Routing Protocol for Wireless Sensor Networks:** We have developed a semantic clustering routing protocol [Bouhafs'05, Bouhafs'06-a, Bouhafs'06-d] that offers a reliable data delivery to the user while reducing both the amount of redundant data transmitted and the resources consumed. In this protocol, a query is propagated towards the nodes which are within the region of a specified event using gradient information routing algorithm. Once found, these nodes form a semantic cluster in order to reduce the amount of redundant data, by means of data aggregation. Unlike current clustering schemes where signal strength and neighbouring information are the most used criteria in the cluster formation, in this work, semantic properties are also taken in consideration in the process of cluster formation. Nodes inside the same cluster are organized like a tree where the cluster-head is the root. This tree organization allows a layered data aggregation, avoids the cluster head overload and offers more energy saving. We evaluated the proposed routing protocol by simulations and showed that our approach is more efficient and data reliable than other communications protocols found in the literature.

- **An Energy-efficient Clustering Protocol for Mobile Event Monitoring in Wireless Sensor Networks:** We have developed a mobile event monitoring protocol based on dynamic semantic clustering that use a cluster membership update scheme [Bouhafs'06-c]. This scheme allows sensor nodes to join or leave the cluster, and cluster head re-election, according to the event mobility instead of new building a cluster around the monitored event, each time it moves, and thus achieving more energy gains and network lifetime extension. Moreover, as event may split into two or more new sub-events, we propose a cluster split scheme that allows the user to monitor the event split and the resulting new events. We evaluated the proposed protocol by simulations and showed that our approach is more energy efficient than other approaches. Simulations assessed also the efficiency of the cluster split scheme proposed in this work and showed its effectiveness.

- **A Node Recovery Scheme for Data Dissemination in Wireless Sensor Networks:** In this work we proposed a node recovery scheme that helps to maintain the data dissemination robust against energy exhaustion of sensor nodes [Bouhafs'06-e]. The proposed scheme exploits the network density and the broadcasting nature of the wireless medium to replace the energy depleted sensor nodes by other neighbouring nodes. These neighbouring nodes must have the ability to relay the data from the source to the destination. Our recovery scheme can work with any gradient-based routing protocol. We evaluated this work by simulations and showed that our approach improves the communication reliability and extends the routing path lifetime. The simulations showed also that our scheme is more reliable and more energy efficient than other data dissemination approaches found in the literature.

- **A Coordination Framework for the Single Actor Model in Wireless Sensor and Actor Networks:** In this work we considered the problem of coordination between sensor nodes for the single actor model [Bouhafs'06-b, Bouhafs'06-c, Bouhafs'06-d]. In this model, once an event is detected, there is only one actor that needs to be informed. This model is very important as it helps to avoid coordination between actors and reduces the number of exchanged messages, thereby reducing the energy consumption. We proposed a coordination framework based on semantic clustering scheme. In this framework, nodes are initially organized in Voronoi diagram, where each actor builds a Voronoi region containing its nearest sensor nodes. Once an event is detected, sensor nodes within the event area are grouped using our semantic clustering protocol and the nearest node to the event source is elected as cluster head in order to inform the nearest actor. We analyzed the proposed framework by simulations and showed that our approach fulfils the single actor condition while achieving good energy saving and acceptable time delay.

1.7 Thesis Structure

This thesis is organized as follow:

- In Chapter 1, we introduce the problem of communication in wireless sensor networks. We first outline the characteristics of wireless sensor networks and requirements. We highlight the resources constraints of wireless sensor networks and the need of new energy efficient and application specific routing protocols for wireless sensor networks. Then, we describe the four major issues in routing for wireless sensor networks. Finally, we outline the aims and the contributions of our work, and the structure of the thesis.

- In Chapter 2, we survey the existing routing and communication protocols for wireless networks in general and wireless sensor networks in particular. This chapter presents a background on wireless sensor and actor networks, data aggregations algorithms and semantic routing. In this chapter we describe also the environmental and radio energy models we used as a basis for our work.

- In Chapter 3, we overview our proposed communication mechanisms, the role of each component, and how these components are integrated together to deliver the goal of our project.

- In Chapter 4, we explain with details our new proposed semantic clustering routing protocol for wireless sensor networks which includes the query dissemination scheme as well as the semantic clustering scheme. In this chapter, we analyse the features of the proposed protocol, and we compare it with other existing routing approaches.

- In Chapter 5, we discuss the clustering routing protocol for monitoring mobile events in wireless sensor networks. This chapter describes the design of this protocol and shows its advantages through simulation.

- In Chapter 6, we present our node recovery scheme; we study the conditions that affect the performances of this scheme and show through both mathematical analysis and simulations the effectiveness of our scheme. In this chapter we show also how our scheme can improve the data delivery quality and the network connectivity.

- In Chapter 7, we present and overview our coordination framework for wireless sensor and actor networks, we describe its different phases, and evaluate it by simulations.

- In Chapter 8, we conclude our dissertation, by summarizing the finding and the problems that we had so far, discuss the major issues and future work in the area of wireless sensor networks.

2 Background

The simplest perception one has of a wireless sensor network is a pool of densely distributed sensors that can be used to retrieve any kind of information related to the local environment where it has been deployed. Such networks are foreseen to be one of the most exciting and challenging technologies to meet the growing demands for accurate data gathering and efficient communication in a large variety of applications: habitat monitoring, health, security, etc.

Recent developments in sensor technology and low power radios have enabled the widespread deployment of wireless sensor networks. These networks consist of small sensor nodes with sensing, computation, communication and actuation capabilities. An individual sensor node collects data from the environment, performs local processing of these data including quantization and compression, and communicates its results to the user via a wireless medium. Researchers, riding on this advance, expect that wireless sensor networks will become smaller, cheaper and thus deployed in large number. By distributing sensor nodes spatially, the wireless sensor network could provide better coverage, faster response to dynamically changing environments, better survivability, and robustness to failure.

Ecologists can monitor air pollution clouds, receiving updates of both location and ambient environmental conditions every few seconds. Forest fire fighters can deploy highly sensitive temperature sensors to detect any abnormal temperature rising and prevent any fire before it spreads. Security land services can deploy chemical or radioactive sensors in big building and public places to prevent any chemical or radioactive attack.

Typically, each node in a sensor network operates untethered, and it is equipped with a microprocessor, one or more sensing devices (sound sensor, temperature sensor, etc), and limited amount of memory. A sensor node is also energy limited, and communicates wirelessly with the other sensor nodes within its radio range.

Considering these characteristics many issues need to be addressed in order to meet the applications performances requirements:

Resources limitation

As sensor nodes are battery operated and the wireless spectrum offers small bandwidth for transmission, it is necessary to design new resource aware communication protocols capable to adapt to these harsh constraints.

Spatio-tempral correlation

Wireless sensor networks are characterized by the dense deployment of sensor nodes that continuously observe physical phenomenon. Due to high density in the network topology, sensors observations are highly correlated. Therefore, it is necessary, to reduce the amount of redundant information in order to save scarce resources.

Data-centric naming:

Since sensor nodes are deployed with sheer number, assigning an address to each node becomes not feasible. Moreover, sensor nodes are usually queried according to their reading and individual observations. Thus, data-centric naming needs to be used instead of traditional address-based naming.

In this chapter we investigate the research efforts found in the literature on communication protocols for wireless networks in general and the recent work on wireless sensor networks in particular. We will also present several concepts related to our work.

In section 2.1, we survey the communication protocols developed by research community to support an energy efficient and long life wireless sensor networks. In section 2.2 we present an overview on major work related to routing in wireless networks found in the literature and expose their main drawbacks and explain why these protocols are not suitable for wireless sensor networks. Then in section 2.3 we describe the main two categories of routing protocols for wireless sensor networks found in the literature, namely, data-centric routing and hierarchical clustering routing. In section 2.4 the role of data aggregation in wireless sensor networks, how this technique works and how it can help to achieve high data accuracy and better resources saving are explained. We introduce the semantic routing paradigm and describe its proprieties, in section 2.5. In section 2.6 we discuss the problem of routing in mobile event monitoring applications using wireless sensor networks, expose the main issues related to this field, and the existing solutions found in the literature. In section 2.7 we expose the coordination problem of wireless sensor and actor networks and present the different modes of operation for such networks. We also describe the environmental model and the radio energy model assumed in our work in section 2.8 and 2.9 respectively. Finally, we present our summary in section 2.10.

2.1 Communication in Wireless Sensor Networks

Since both device and battery technologies have only recently matured to the point that sensor nodes are feasible, this is a fairly new field of study. Researchers have begun discussing not only the uses and challenges facing sensor networks, [Pottie'00] but also have been developing preliminary ideas as to how these networks should function [Chandrakasan'99, Cheek'05, Clare'99] as well as the appropriate low-energy architecture for the sensor nodes themselves [Bult'96, Dong'97, Vieira'03].

Sensor nodes typically contain a sensor module, some sort of processing element and a wireless interface module [Cheek'05]. As these nodes are battery-operated it is important to ensure each of these modules is low-power to extend nodes lifetime. Some techniques have been proposed to manage the power consumption [Min'00] [Sinha'01] [Dong'97] [Hui'03 , O'Hare'05]. However, all these techniques might be without any benefits if the communications protocols are not energy-efficient as well.

Thus, in addition to developing low-energy hardware, it is important that wireless sensor networks use low-energy protocols. The challenge of designing a new communication protocols set for wireless sensor networks has attracted a lot of attention in the past few years and many projects have been created in this aim [μ-AMPS'99, Awairs'00, Kahn'99-a, Scadds'00, Smartdust'00, UAMPS99, Wins'00].

The authors in [Heinzelman'99] developed SPIN (Sensor Protocols for Information via Negotiation), a family of protocols to disseminate information in wireless sensor network. In SPIN, large data messages are named using high level data descriptors, called meta-data. In this architecture, nodes use meta-data negotiation to eliminate the transmission of redundant data through the network. Allowing nodes to base routing decisions on application-specific information about the data, enables large energy savings compared with conventional approaches.

Another low-energy protocol architecture for wireless sensor networks was developed by Clare *et al.* [Clare'99] as part of the AWAIRS (Adaptive Wireless Arrays for Interactive Reconnaissance, Surveillance, and Target Acquisition in Small Unit Operations) wireless sensor network project [Awairs'00]. This architecture enables self-organizing of the network and uses a TDMA MAC approach for low-energy communication. In this architecture, the first two nodes alive form the initial network, and each discovered node will join the network. Each node is given several TDMA slots in which it can transmit data to its neighbours through point-to-point communications or broadcasting, and each node also knows when it must be awake to receive data (either sent unicast or broadcast) from all of its neighbours. This architecture allows the nodes to remain in the sleep state, with radios powered down, for a large amount of time.

The μ-AMPS (Micro-Adaptive Multi-domain Power-aware Sensors) project [μ-AMPS'99] aims to develop a framework for implementing adaptive energy-aware distributed wireless sensor nodes. The goal of this project is to provide an energy-efficient and scalable solution for a range of sensor applications. This involves designing innovative energy-optimized solutions at all levels of the system hierarchy including: physical layer (e.g transceiver design), data-link layer (packetization and encapsulation), media access layer (multi-user communication with emphasis on scalability), network/transport layer (routing and aggregation schemes), session/presentation layer (real-time distributed OS), and application layer (innovative applications).

Several institutions have begun large-scale projects to develop new communication protocols and mechanisms for wireless sensor networks. These projects include:

- AWAIRS: Adaptive Wireless Arrays for Interactive Reconnaissance, Surveillance, and Target Acquisition in Small Unit Operations [Awairs'00] [Clare'99]
- WINS: Wireless Integrated Network Sensors [Pottie'00, Wins'00]
- Smart Dust: Autonomous Sensing and Communication in a Cubic Millimetre [Kahn'99-b] [Smartdust'00]
- Tiny OS: Operating System for Embedded Sensor Networks [Tinyos'03]
- SCADDS: Scalable Coordination Architecture for Deeply Distributed Systems [Estrin'99, Scadds'00]
- μ-AMPS: Micro-Adaptive Multi-domain Power-aware Sensors [μ-AMPS'99]
- PicoRadio: Wireless Sensor Network research at the Berkeley Wireless Research Center [Rabaey'00] [Picoradio'00]
- wsLAN: wireless sensor Local Area Network [wsLAN'03]
- SensEye: A Multi-tier Camera Sensor Network [Kulkarni'05-a, Kulkarni'05-b]

In addition, there are numerous projects to develop "ubiquitous computing" architectures. Researches predict that the future of computing is one where computers are everywhere, but at the same time invisible to the user [Borriello'00]. Distributed and embedded wireless sensor networks (as well as wireless sensor and actor networks) will be essential technology to enable the full integration of computers into our daily lives.

2.2 Routing Protocols for Wireless Networks

The past several years have shown a wealth of new protocols for wireless networks, including both routing and MAC protocols. Several standards have been proposed to facilitate interoperability among different devices in a wireless network.

For example, the IEEE 802.11[ICSLMC'99] standard specifies a MAC protocol that was designed to minimize the probability of collision. Other standards such as HomeRF [Lansford'00] and Bluetooth [Haartsen'00] specify the entire wireless network stack. Typically the stack layers are implemented independently. This allows the communication architecture to be broken in layers, with each layer operating independently and providing a defined support to the layers above.

Routing protocols design in wireless networks has been significantly influenced by existing routing protocols in wired networks such as the Internet. Routing protocols for wired networks fall into two main categories: distance vector routing and link state routing [Huitema'00]. In distance vector routing approaches, each node advertises distances to its neighbours, who then choose the shortest path to a given destination and store this information in a routing table. As a packet comes to the node, it looks in its routing table to determine the next hop to get the packet to its destination. In link-state approaches, on the other hand, nodes save a copy of the entire topology map, and each node uses a shortest path algorithm such as Dijkstra algorithm to find the best node to the destination. These routing approaches have been incorporated into wireless networks by introducing minor modifications, resulting in destination-sequenced distance vector (DSDV) [Perkins'94] and ad hoc on-demand distance vector (AODV) [Perkins'99]. However, the main drawback of these routing protocols is the large number of control messages transmitted periodically in order to maintain valid routes, which may not only congest the network but also drain the nodes limited energy. Dynamic source routing (DSR) [Broch'98] solves this problem by only creating routes on an on-demand basis. This minimizes the amount of overhead needed in creating routes, at the expense of latency in finding a route when it is needed.

Work has been done on low power routing protocols to extend the lifetime of the portable devices in a wireless network. The author in [Meng'98] discusses a strategy for choosing multihop routes to minimize power dissipation in the nodes along the route. In this approach an intermediate node is used as a hop if and only if it minimizes the total energy compared with not using this hop node. A similar work is proposed in [Scott'96] in which the authors note that, transmission between neighbouring nodes in wireless networks causes interference, which can degrade its performance. Hence, they choose routes to minimize energy dissipation subject to a minimum interference criterion.

The Self-Organizing Wireless Adaptive Network (SWAN) protocol [Scott'95] uses dynamic topology management with power control to deform the network gradually instead of having the network periodically broken and rebuilt. This allows data to experience a minimum amount of delay and no outages due to network recovery functions.

Recently, there has been much work on power-aware routing protocol for wireless networks [Chang'00, Li'01, Singh'98] . In these protocols, optimal routes are chosen based on the energy at each node along the route. Routes that are longer but use nodes with more energy than the nodes along the shorter routes are favoured. This helps to avoid hot-spots in the network, where a node is often used to route other nodes' data, and it helps to evenly distribute energy dissipation.

Another approach of communication in wireless networks is to use a clustering approach, similar to a cellular telephone. In this approach, nodes send their data to a central cluster head that forwards the data to get it closer to the desired recipient. Clustering has been used initially in wireless networks to enable bandwidth reuse and thus increasing the network capacity. Using a clustering approach enables better resource allocation and helps improve power control [Kwon'99]. In addition, the hierarchical structure obtained using clustering can help to overcome some of the problems with node mobility.

While conventional cellular networks were designed to work on a fixed infrastructure [Garg'95], researchers started focusing on ways to deploy clustering architectures in ad-hoc fashion, without the assistance of a fixed infrastructure [Baker'84, Kwon'99, Lin'97]. Early work in [Baker'84] developed a link cluster architecture where using the distributed linked cluster algorithm (LCA), nodes are assigned to be ordinary nodes, cluster-head nodes, or gateways between different clusters. The cluster-head acts as a local control centre, whereas the gateways act as the backbone network, transporting data between clusters. This enables robust networking with point-to-point connectivity. A similar system, the Near Term Digital Radio (NTDR)

[Ruppe'97] uses a clustering approach with a two-tier hierarchical routing algorithm. In this routing algorithm, nodes are firstly grouped in clusters, where in each cluster nodes can communicate directly using a multihop routing approach. In the case of an inter-cluster communication, the data is routed through the cluster head nodes. In this protocol, the cluster head nodes change as nodes move in order to keep the network fully connected. This protocol, designed to be used for a wireless data network, enables point-to-point connectivity.

In [Lin'97] authors develop a fully distributed cluster formation and communication algorithm where there are no fixed cluster-head nodes in the cluster. This has the advantage of avoiding bottlenecks in the network. This distributed cluster formation uses a lowest-node-ID algorithm, whereby the cluster-head position is assigned to the node with the lowest of its ID and all its neighbours IDs. A cluster maintenance algorithm is created to ensure connectivity of all nodes in the presence of node mobility, and a combination of TDMA/CDMA scheme is used to ensure minimum inter-cluster and intra-cluster interference.

Power control can be used to dynamically adjust the size of clusters [Kwon'99]. If open-loop power is used, the cluster head node sends out a beacon, and nodes that hear the beacon join the cluster. If there are too many nodes in the cluster, the cluster head can reduce the beacon signal strength so fewer nodes will hear it. On the other hand, if the cluster is too small, the cluster head can increase its beacon signal strength to increase the membership. New clusters may be formed when a cluster head decreases its membership size, and clusters may be merged when a cluster head increases its membership size in order to keep the network fully connected.

In [McDonald'99] the author develops a clustering algorithm that enables good routing while supporting node mobility and stability. Their (α,t) cluster algorithm creates clusters of nodes where the probability of path availability is bounded over time. This allows the clustering algorithm to adapt to node mobility, creating more optical routing under low mobility.

Although the proposed protocols for wireless networks consider energy, bandwidth and time delay constraints they are still not suitable for sensor networks for the following reasons:

- The routing protocols proposed for wireless networks generate an important amount of control traffic that may consume too much energy. Knowing the energy constraint of wireless sensor networks, these protocols can not be considered energy efficient.

- Routing protocols proposed for wireless networks do not take into consideration the data-centric nature of wireless sensor networks. Indeed, unlike the traditional IP networks, wireless sensor networks are data-centric based networks where the user, usually, sends a query that describes its data interest, through the network and only nodes that satisfy this query reply to the user.

- Routing in wireless networks is usually between any two devices, while in wireless sensor networks, routing is between a group of sensor nodes and the sink.

Therefore, wireless sensor networks need a new generation of routing protocols able to satisfy the user requirements while saving the scarce resources as much as possible. These new routing protocols will be completely different from traditional routing techniques based on shortest path discovery algorithms and low-bandwidth. Routing in wireless sensor networks involves new factors specific to the application such as the user query or nodes data attributes. Moreover, as nodes are, usually, densely deployed and the collected data is expected to be highly correlated, techniques like in-network data aggregation and processing need to be used to reduce the amount of data sent to the sink and overcome scalability and the resources constraints. In the next section we will describe the main routing protocols for wireless sensor networks found in the literature, their features, advantages and drawbacks.

2.3 Routing Protocols in Wireless Sensor Networks

Routing is one of the most important challenging tasks in wireless sensor networks. It has attracted a lot of attention in recent years. Several routing mechanisms have been proposed and can be classified into two major types: Data-centric routing, and Hierarchical clustering routing, although there are few distinct ones based on sensor nodes location, network flow or quality of service (QoS) awareness [Akkaya'05]. In the remaining part of this section we will review the related work in these two categories.

2.3.1 Data Centric Routing

In wireless sensor networks there are many applications built on a query-based system. In this type of applications, a wireless sensor network consists of one or more "sinks" which subscribe to specific data streams by expressing interest or queries. The sensor nodes in the network act as "sources" which detect environmental events and push relevant data to the appropriate subscriber sinks.

A classic approach to this problem is to use flooding [Hedetniemi'88] where each node wishing to disseminate data across the network starts by sending a copy to all its neighbours. Whenever a node receives new data, it makes copies of the data and sends the data to its neighbours, except the node from which it just received the data. The amount of time it takes a group of nodes to receive some data and then forward that data to their neighbours is called a *round*. The algorithm finishes, or *converges*, when all the nodes have received a copy of the data. Flooding converges in *O(d)* rounds, where *d* is the diameter of the network, because it takes at most *d* rounds for a piece of data to travel from one end of the network to the other. The flooding approach exhibit three deficiencies that render it inadequate for wireless sensor networks [Heinzelman'99]:

- **Implosion:**
  In classic flooding, a node always sends data to its neighbours, regardless of whether or not the neighbour has already received the data from another source. This leads to the implosion problem, as it is illustrated in figure 2-1. Here, node A starts out by flooding data to its two

neighbours: B and C. These nodes store the data from A and send a copy of it on to their neighbour D. The sending of the two copies results in waste of energy.

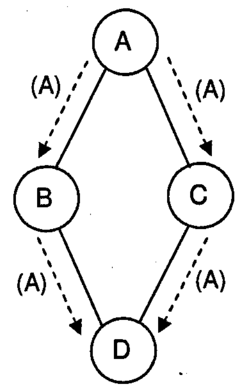


Figure 2-1: The implosion problem

- **Overlap:**

  Sensor nodes often cover overlapping geographic areas, and nodes often gather overlapping pieces of data. Figure 2-2 illustrates an example where two sensor nodes cover two overlapping areas. In such case the data gathered by the two sensor nodes contain some redundancy. Knowing the energy constraints of sensor nodes, it is important to eliminate such redundancy in order to save scarce resources. Therefore, overlapping problem, like implosion, results in waste of energy. However, while implosion problem is related to network topology, overlapping problem is related to network topology and the mapping of observed data to sensor nodes.

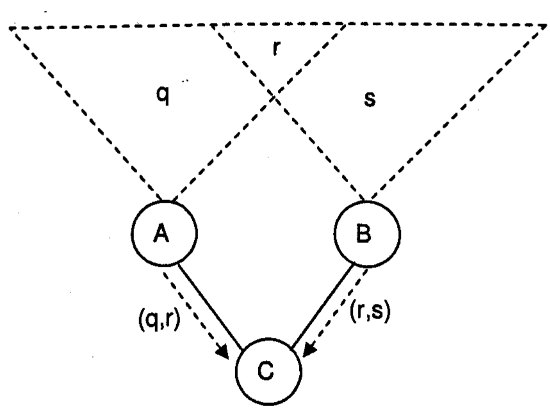


Figure 2-2: The overlap problem

- **Resource blindness:**
  In classic flooding, nodes do not modify their activities based on the amount of energy available to them at a given time. A sensor network should be resource-aware and adapts its communication and computation according to its energy resources.

Gossiping [Hedetniemi'88] is an alternative to the classic flooding approach that uses randomization to conserve energy. Instead of indiscriminately forwarding data to all its neighbours, a gossiping node forwards data on to one randomly selected neighbour. If a gossiping node receives data from a given neighbour, it can forward data back to that neighbour if it randomly selects that neighbour, as illustrated in figure 2-3.

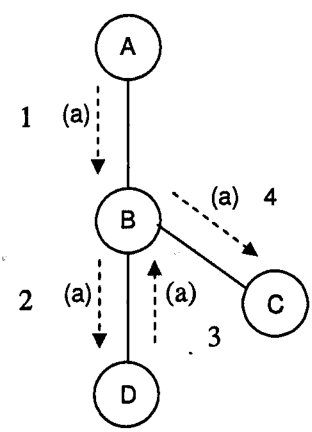


Figure 2-3: Example of gossiping approach

If node D never forwarded the data back to node B, node C would never receive the data.

The gossiping technique avoids the problem of implosion and thus does not waste as much network resources as flooding. However, as neighbour nodes in gossiping are chosen randomly it is possible that some nodes in the large network may not receive the message at all. Therefore, gossiping is not a reliable method for data dissemination.

In data-centric routing, the sink 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 it is necessary to specify the properties of data. SPIN (Sensor Protocols for Information via Negotiation) [Heinzelman'99] is the first data-centric routing protocol which consider data negotiation between sensor nodes in order to eliminate redundant data and save energy. In SPIN a high-level descriptors or meta-data are exchanged among sensors via a data advertisement mechanism before data transmission. Each node, upon receiving new data advertises it to its neighbours. Interested neighbours, i.e. those who do not have the data, retrieve the data by sending a request message. By using the meta-data negotiation SPIN guarantees that data messages are sent to the interested neighbour nodes only. Therefore, SPIN avoids implosion and achieves a lot of energy efficiency. However, SPIN's data advertisement mechanism cannot guarantee the delivery of data all the time. For instance, if the nodes that are interested in the data are away from the source node and the nodes between source and destination are not interested in that data, such data will not be delivered to the destination at all.

Directed Diffusion [Intanagonwiwat'00, Intanagonwiwat'03] is another data-centric communication paradigm where a sink sends out a request for data by broadcasting an interest to its neighbouring nodes. An interest refers to a named description of a service that a sink node requires. The neighbours subsequently broadcast the interest to their respective neighbours and this process is repeated until a source node, which is capable of servicing the request, comes across the interest. As interests diffuse throughout the network, a node that receives an interest from a neighbouring node forms a gradient pointing to the sending node that indicates the direction in which data from a source node will eventually flow. The source node then generates data messages using its sensors which propagate back to the sink following the gradients formed along the paths through which the interest originally traversed. Every sink that receives data messages from more than one neighbour, reinforces a particular neighbour so that subsequent data messages arrive only from the chosen neighbour. This chosen neighbour also performs the same procedure on its neighbouring nodes it received a data message from. This process is repeated until data messages propagate only along the reinforced path from source to sink. If the quality of data transmission from a certain neighbour deteriorates, a node can opt to negatively reinforce another better-performing neighbour instead, in order to cope with varying network dynamics. Many other protocols have been proposed either based on Directed diffusion [Braginsky'02, Chu'02] or following a similar concept [Sadagopan'03, Yao'02].

The main drawback of such approach is the flooding technique used to propagate the user interest. Recall that sensor nodes are power constrained and the wireless medium allows a small bandwidth for transmission and reception of data. Therefore, flooding the whole network in order to find the source nodes may lead to early nodes exhaustion and the lost of the network connectivity. In addition, the data-centric routing approach does not propose any organization scheme between source nodes once found, which may lead to the transmission of a large number of redundant data messages.

2.3.2 Hierarchical Clustering Routing

The second category of routing protocols in wireless sensor networks is hierarchical clustering. The main function of the wireless sensor networks is the transport and gathering of information. However, these networks are limited in, energy, bandwidth, etc, and the challenge is to optimize the deployment of these networks as well as the gathering of the data. The clustering approach which is borrowed from the cellular telephone networks, has been used to tackle these constraints.

Hierarchical clustering routing approach maintains the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster. Cluster formation is based, generally, on the energy reserve of sensors and sensor's proximity to the cluster head [Buczak'98]. The low-energy adaptive clustering hierarchy (LEACH) protocol developed in [Heinzelman'00, Heinzelman'02] is one of most popular hierarchical routing algorithms in wireless sensor networks. The idea is to form clusters of sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. Data aggregation and fusion are local to the cluster, this will save energy since the transmissions will only be done by such cluster heads rather than all sensor nodes. Cluster heads change randomly over time in order to balance the energy dissipation of nodes. The idea proposed in [Heinzelman'00, Heinzelman'02] has been an inspiration for many hierarchical routing protocols [Lindsey'03, Manjeshwar'01, Manjeshwar'02].

The protocol proposed in [Lindsey'03] is an improvement of [Heinzelman'00], where rather than forming multiple clusters, this protocol forms chains from sensor nodes so that each node transmits and receives from neighbours and only one node is selected from that chain to transmit to the sink. For gathering data in each round, each node receives data from one neighbour, fuses it with its own data and transmits the result to other neighbour in the chain. The dissemination of interest messages in [Chatterjea'03] only involves the cluster heads and the gateway nodes and every node of them contains an interest cache containing an entry for each single distinct interest message it receives. In order to reduce duplicated data propagated through the network. This protocol uses a layered data aggregation at different points of the sensor network.

The most important issue regarding these protocols is that they cannot be used in query-based applications where the user is interest in gathering data from a certain group of sensor nodes that satisfy a certain condition. Another issue regarding is how to form the clusters so that the energy consumption within a cluster is optimized. This issue leads us to question of how we can deliver data from sensor nodes to their leader node. The simplest way is to send all data records directly to the leader along multi-hop routes, and to do all the computation directly at the leader. This is a reasonable solution for small networks. However, if we consider the computation of aggregates over larger regions, this scheme will generate many messages and consume a lot of power. Thus, it is important to find a new efficient intra-cluster data dissemination mechanism [Akkaya'05].

2.4 Sensor Data Aggregation

The sensor data are different from the data associated with traditional wireless networks in that it is not the actual raw data itself that is important; rather, the information resulted from the analysis of the data, which allows the user to determine something about the environment that is being monitored, is the important result of the sensor network. For example, if the sensor nodes are monitoring an area for surveillance purposes, the user does not need to see the individual sensors data but does need to known if there has been an intrusion in the area being monitored. Therefore, it is necessary to use automated methods of data processing called *data aggregation* in order to produce a small set of meaningful information [Brooks'98 , Hall'92]. In addition to helping avoid information overload, data aggregation, also known as data fusion, can combine several unreliable data measurements to produce a more accurate signal by enhancing the common signal, reducing the uncorrelated noise, and eliminating the redundancy. The classification performed on the aggregated data might be performed by a human operator or automatically. Both the method of performing data aggregation and the classification algorithm are application-specific.

In a conventional sensor network, all the data X are transmitted to the sink, where they are processed (aggregated) to receive the data $f(X)$. Automated methods can then be used to classify this aggregate signal. However, the function f can sometimes be broken up into several smaller functions f_1, f_2,....,f_n that operate on subsets of the data X_1, X_2, ..., X_n such that:

$$f(X) \approx g(f_1(X_1), f_2(X_2), \ldots\ldots, f_n(X_n))$$

One method of aggregation data is called *beamforming* [Yao'98]. This method combines signals from multiple sensors as follows:

$$y[n] = \sum_{i=1}^{N} \sum_{l=1}^{L} w_i[l] s_i[n-1]$$

Where s_i [n] is the signal from the ith sensor, w_i[n] is the weighting filter for the ith signal, N is the total number of sensors whose signals are being beamformed, and L is the number of taps in the filter. The weighting filters are chosen to satisfy optimization criteria, such as minimizing mean squared error (MSE) or maximizing signal-to-noise ratio (SNR). Various algorithms, such as least mean squared (LMS) error approach and the maximum power beamforming algorithm have been developed to determine good weighting filters. These algorithms have various energy and quality tradeoffs [Wang'99]. For example, the maximum power beamforming algorithm is capable of performing blind beamforming where sensor nodes' data are aggregated regardless of their degree of correlation. However, this algorithm is computation-intensive, which will quickly drain the limited energy of the node. By determining the amount of computation needed to fuse the data from several sensor nodes and the associated energy and time costs to perform these signal processing operations, it is possible to determine the optimum tradeoffs between computation and communication.

While data aggregation can be put forward as a useful paradigm for routing in wireless sensor network, this technique requires the formation of groups of sensors to control the data gathering and aggregation and thus, save more energy. However, grouping nodes according to their neighbouring properties is not sufficient to guarantee an efficient data aggregation and an accurate result. Therefore, it is necessary to consider the semantic properties of sensor nodes before performing grouping and data aggregation operations.

2.5 Semantic Routing

In many wireless sensor networks applications the user's query or the application task may inherently specify a limited logical scope and defines the nodes involved in this task or which nodes should answer the user's query. Rather than flooding the entire network, the querying system and the networking layer might instead coordinate to provide efficient data dissemination and semantically scope floods. A query system may define some policies so query messages are delivered only to nodes that satisfy a particular application's condition or user' query. As an example, the semantic tree proposed in [Madden'03] allows query dissemination to be scoped to nodes whose readings are within a particular range, avoiding unnecessary query forwarding and reducing flooding overhead. Another example of semantic routing can be found in [Zhao'04], where for target tracking, the author proposes to discover querying paths to nodes close to the target by optimizing an objective function that balances the usefulness of the sensor data and the corresponding communications costs along the paths.

However, these benefits are in contradiction with current routing approaches where paths between sources and sinks are optimized for reliable and shortest-path delivery. In order to achieve a more data aggregation and correlation opportunities, it may be better for the query processing system to choose less reliable paths, as such paths can reduce the overall transmission load on the network.

Recall that sensor networks are applications specific, and information collected by nodes are highly correlated, thus, an ideal routing protocol would be able to exploit in-network processing as much as possible while still delivering the end results to their destinations. Such routing protocol would consider both the semantic information from the query or the task and link-layer reliability and connectivity properties learned from neighbouring nodes.

2.6 Routing in Mobile Event Monitoring Applications

One of the major application categories of wireless sensor networks is the monitoring of events that may occur in the physical environment. In these applications, the sensor nodes are requested to gather information about a specific phenomenon upon detected and send this information to the user. However, in many of these applications the monitored event can be mobile such as toxic cloud or radioactive mobile object [Stephens'04, Tsujita'04]. Knowing the characteristics of wireless sensor networks and the related communication issues, designing a routing protocol for this kind of applications is very challenging.

Routing for mobile event monitoring applications have attracted a lot of attention in the recent years [Brooks'03, Li'02, Nemzek'04, Stephens'04, Tseng'03]. In [Zhao'02] an information driven sensor collaboration mechanism is proposed. In this mechanism, measures of information utility are utilized to decide future sensing actions. Collaborative signal processing aspects for target classification in sensor networks is addressed in [Li'02]. Tracking based on relations in the targets is discussed in [Brooks'03]. Techniques for locating targets using a variety of mechanisms have been proposed in [Butler'03, Tseng'03]. However, these approaches do not address the issue of sensor nodes coordination for the purpose of target tracking, nor consider the minimization of computation and communication overheads in such systems.

Recently works on target tracking based on clustering have been proposed [Chen'04, Fang'03]. In [Chen'04] an acoustic target tracking clustering protocol is proposed. Sensor nodes detecting an acoustic signal with a certain threshold report their data to a high capability node which groups the nearest nodes detecting the same signal in a cluster. While the tracked object is localized with precision, this work does not consider the energy constraint as it assumes a heterogeneous wireless sensor networks containing a number of highly capable sensor nodes. The protocol proposed in [Fang'03] follows a similar approach by grouping sensor nodes detecting the same event in an aggregate. Before joining the aggregate, each node needs to apply a decision predicate, using a distributed algorithm. A node declares itself a cluster leader if it finds that it has the higher signal than all its one hop neighbours, then all cluster members will send their information to it.
However, the main drawbacks of these approaches is that they do not update the cluster when the tracked target changes positions, but instead they destroy the previous cluster and create a new one. In situations where the tracked target is moving very fast; this operation might cause a significant communication overhead and waste too much energy.

2.7 Wireless Sensor and Actor Networks

Although wireless sensor networks were designed initially to detect and monitor physical events, they could be used actively by deploying active nodes called *actors*. Actors are nodes that could perform actions in the study field according to the information collected by sensor nodes. In Wireless sensor and actor networks, sensor nodes are generally deployed to retrieve data from the study field and inform actor about any physical event detected in the environment. These networks have many applications, such as: battlefield surveillance, fire protection, chemical attack detection, etc.

Typically, sensor nodes in these type of networks have the same characteristics as in wireless sensor networks, which means they are equipped with a microprocessor, one or more sensing devices (sound sensor, temperature sensor, etc), and limited amount of memory. Sensor nodes are also energy limited, and communicate wirelessly with the other sensor nodes within its radio range. However, actors are, generally, mobile, energy-rich, equipped with better processing and transmission capabilities, and sparsely deployed comparing to sensor nodes which are densely deployed.

Wireless sensor and actor networks design is aiming to perform the adequate action correspondent to the detected event with higher precision. Upon a detection of an event a sensor node must signal this event to an actor to deal with it. Wireless sensor and actor networks could be used in two modes, automated mode and semi-automated mode as it is illustrated in figure 2.5.

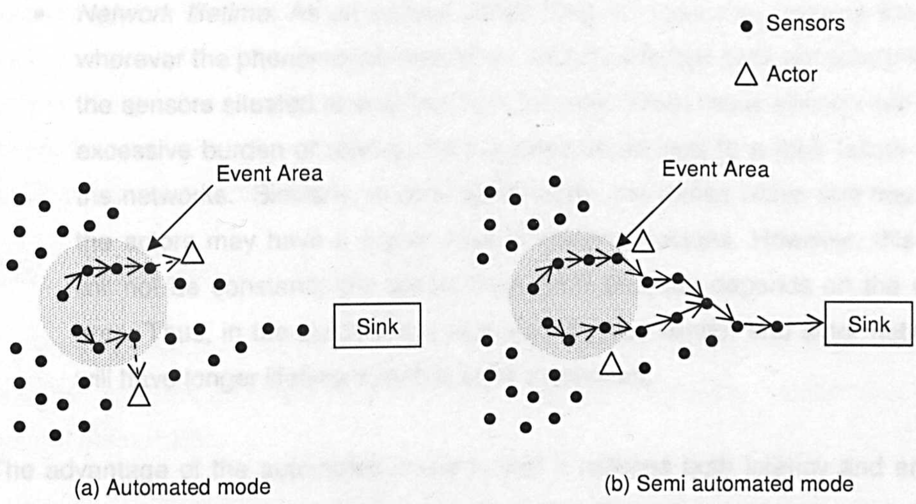


Figure 2-4: Wireless sensor and actor networks architecture

➢ *Automated Mode*: In this mode, sensor nodes detecting a phenomenon send their collected data to the actor nodes which process all incoming data and initiate appropriate actions.

➢ *Semi-Automated Mode*: In contrast to the automated mode, in this mode all sensors send their data to the sink which will coordinate all the acting process with actor nodes.

The two modes have their advantages and drawbacks. The advantage of the semi-automated mode is that it is has an architecture similar to the architecture used in wireless sensor networks, thus actual works on routing and communication schemes could fulfil the requirement of such networks. However this mode has two major drawbacks:

- *Latency*: If an phenomenon is detected by some sensor nodes, performing an action towards this phenomenon will take time since each node has to send its data to the sink and each actor has to wait until it receive orders from the sink. In automated-mode such latency will be less important since sensors send their data to actors directly.
- *Network lifetime*: As all sensor nodes have to send their data to the sink wherever the phenomenon happened, all the collected data will pass through the sensors situated at one hop from the sink. Thus, these sensors will have excessive burden of relying. Such burden could lead to a total failure of all the networks. Similarly, in automated-mode, the nodes within one hop from the actors may have a higher load of relaying packets. However, this load will not be constantly the same since such situation depends on the event area. Thus, in the automated-mode the wireless sensor and actor networks will have longer lifetime than the semi-automated.

The advantage of the automated mode is that it reduces both latency and energy consumption, as it does not imply any communication between sensor nodes and the sink.

For the automated mode there are two models for communication between the sensors and actor nodes: single actor model and multiple actors' model. In the single actor model only one actor is called when an event is detected while in multiple actors' model it is assumed that sensor nodes can call many actors. The single actor model is simpler to implement, while the multiple actor's model requires coordination between actor nodes. However, the use of this model emphasises the necessity for a coordination solution between all nodes. Indeed, in the case where a specific event is detected as both sensor and actor nodes are assumed to work in distributed way and without any central monitoring station, it is important to coordinate the communication between those sensor nodes which detected the event so that they inform only the nearest actor to the event area.

One could imagine that sensors-sensors coordination refers to the clustering concepts already well know in wireless sensor networks. However, unlike traditional clustering schemes where clusters are built generally at the deployment of the sensor network, here the clustering must be event-driven. The framework proposed in [Melodia'05] is the first work to propose a distributed event-driven clustering protocol for wireless sensor and actor networks. In this paper the authors propose an event-driven clustering scheme for multiple actors' model in wireless sensor and actor networks. Nodes detecting an event are grouped in a cluster where the nearest actor is the cluster head. Sensor nodes within each cluster are organized in form of d-tree where the cluster head is the root. However this approach considers only multiple actors model. As sensor nodes are densely deployed, in situations where the event area is very small, this model could result in the formation of many small clusters and activation of many actors.

2.8 Case Study: Signal Source Model

Wireless sensor networks can be considered as an interface between the user and the real, through which he can retrieve valuable information, monitor and study natural phenomena.

In some wireless sensor networks applications, sensor nodes are deployed to monitor and track a source of signal, and gather information about the effect of such signal on the local environment. For instance, in radioactive wireless sensor networks [Brennan'05, Tsujita'04] scientist try to track a radioactive source and gather information about it, such as sensing the temperature in the area where the radioactivity signal exceeds a certain threshold.

In such applications where the tracked event is a source of signal, the signal propagation follows the decay law [Leike'02]. This law predict that a signal generated by a source at time t_0 will attenuate exponentially and can be calculated in function of time according to the following equation:

$$n(t) = n_0 e^{\frac{-t}{\tau}} \qquad (2\text{-}1)$$

Where:

n_0 Is the signal amount measured at time t_0.

τ Is the moment when 63% of the initial signal amount has attenuated.

Assuming that the signal generated by the source propagates with a regular speed S, the previous equation can be re-written as following:

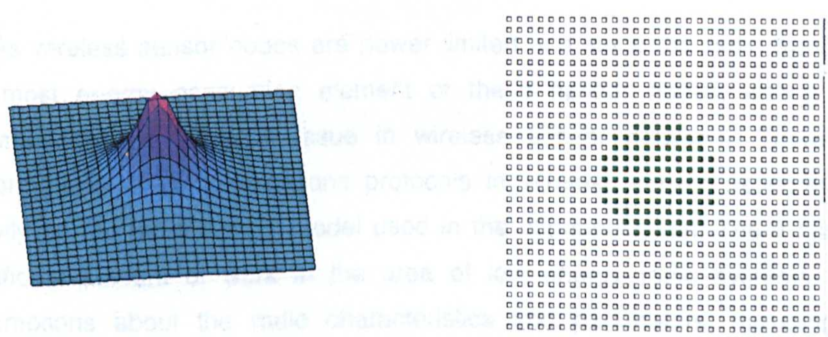
$$n(d) = n_0 e^{\frac{-d}{D}} \qquad (2\text{-}2)$$

Where d Is the distance between the source and the position reached by the signal at time t and D Is the distance between the source and the position reached by the signal at time τ.

If the signal is measured from a distance d, such as $d >> D$, then $-\frac{d}{D} \rightarrow -\infty$, this means that:

$$n_0 e^{-\frac{d}{D}} \rightarrow 0 \qquad (2\text{-}3).$$

From equation (2-3), we can conclude that after a certain distance from the source location, it becomes impossible for the wireless sensor nodes to detect the source signal. The nodes that can detect the source signal form a disk where, the node with the highest reading is the centre of this disk as it is illustrated in figure 2-6.



(a) Event signal propagation (b) Event area

Figure 2-5: Environmental model

The event vicinity could be modelled as a disk where its radius R is defined by the event signal scope [Vuran'04]. We assume that the user is only interested in nodes that detect the event signal with a certain threshold T. As a result, the nodes involved in the communication with the user, will be in a sub-region of the event area that could be modelled by a disk as well, where its radius R_T is lower than the real event area radius R: $R_T<R$, however; these two disks should have the same centre, as it is illustrated in figure 2-7.

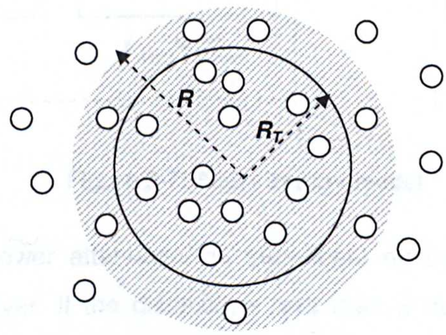


Figure 2-6: Event area and area of interest

In our work we consider applications where the user is interested in tracking and gathering information about a specific physical event that follow the signal source model, and therefore we use this model at the design of our communication mechanisms.

2.9 Radio Energy Model

As wireless sensor nodes are power limited and since the radio transceiver is the most energy consuming element of these sensor nodes, energy efficient communication is a major issue in wireless sensor networks. Therefore, the performances of communications protocols in wireless sensor networks depend heavily on the radio energy model used in the communication. There has been a significant amount of work in the area of low energy radio systems. Different assumptions about the radio characteristics and parameters, including energy dissipation in the *transmit* and *receive* modes, may affect the performance of simulations.

In our work we used the radio energy model proposed in [Heinzelman'02] which is one of the most used models in the wireless sensor networks. This model assumes that the transmitter dissipates energy to run the radio electronics and the power amplifier, while the receiver dissipates energy to run the radio electronics only.

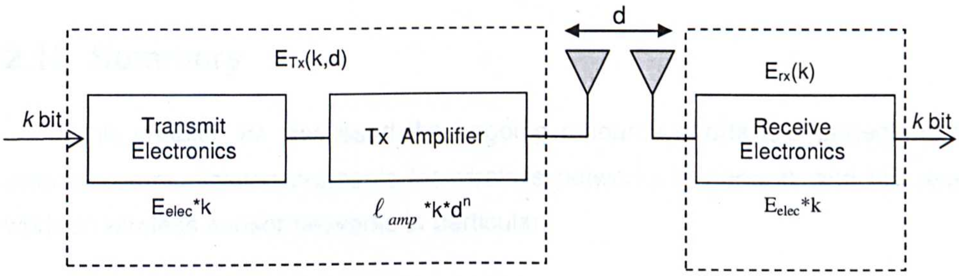


Figure 2-7: Radio energy model

In this model, the power attenuation is dependent on the distance between the transmitter and receiver. If the distance is less than a threshold $d_{crossover}$, the free space (fs) model is used; otherwise, the multipath (mp) model is used. Therefore, for relatively short distances, the propagation model is modelled as inversely proportional to d^2, whereas for longer distances the propagation loss is modelled as inversely proportional to d^4. The power control is used to invert this loss by setting the power amplifier to ensure a certain power at the receiver. Thus, to transmit a k-bit message over a distance *d*, the consumed energy is:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \tag{2-4}$$

$$E_{Tx}(k,d) = \begin{cases} kE_{elec+} + k\ell_{friss-amp} d^2 & : d < d_{crossover} \\ kE_{elec} + k\ell_{two-ray-amp} d^4 & : d \geq d_{crossover} \end{cases} \tag{2-5}$$

And to receive this message, the consumed energy is:

$$E_{Rx}(k) = E_{Rx-elec}(k) \tag{2-6}$$

$$E_{Rx}(k) = kE_{elec} \tag{2-7}$$

The electronics energy E_{elec} depends on factors such as the digital coding, modulation and filtering of the signal before it is sent to the transmit amplifier.

2.10 Summary

In this chapter we discussed the ongoing research efforts and projects in the area of communication protocols for wireless networks in general, and the recent work on wireless sensor networks in particular.

Since wireless sensor networks suffer from harsh resources constraints and are characterized by a dense deployment and lack of a global identification system, it is difficult to design communication protocols for such kind of networks. Although many communication protocols are proposed in the area of wireless networks, these protocols fall short of matching the characteristics of wireless sensor networks and cannot effectively support their applications. Despite the fact that theses protocols consider resources constraints and achieve good energy saving they are not efficient enough to be used in wireless sensor networks.

As wireless sensor networks are, usually, driven by the user data requirement, and since most applications are event-based, the communication protocols must be based on a data-centric routing rather than the address-based routing already used in traditional networks. In most of the proposed data centric routing protocols, the sink sends queries to certain regions and waits for data from the sensors located in the selected regions. However, the flooding technique used in the query propagation makes this routing approach costly in terms of resources.

On the other hand, we find the hierarchical clustering routing approach that tries to maintain the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster. However, although this approach is very energy efficient, the cluster formation used in this approach is based, generally, on the energy reserve of sensors and sensor's proximity to the cluster head. Thus, these routing algorithms built on clustering techniques consider only neighbouring and energy reserve criteria as parameters when forming clusters. Neglecting the user interest and the semantic properties of the sensor nodes 'data would lead to inefficient data aggregation and result in inaccurate information and waste of resources.

The challenge is to design new communication protocol set that enables the user to retrieve highly descriptive information about a certain region or an event detected that occurred in the study field while consuming the minimum possible resources. In this thesis, we present new communication mechanisms for wireless sensor networks based on semantic clustering. These mechanisms take into consideration the following factors: resources, neighbouring information, semantic relevancy to the user requirement, and the nature of the retrieved information or the monitored event. Thus, achieving efficiency and extending network lifetime.

3 Semantic Clustering Mechanisms for Communication

Having introduced existing communications and routing protocols for wireless sensor networks, we now present the outline of our proposed work. In section 3.1 we summarize and highlight the main issues and problems related to routing and the communication challenges while designing applications in wireless sensor networks. In section 3.2 we present our new communication mechanisms. The simulations environment used in our work is described in section 3.3. Finally, a summary of this chapter is provided in section 3.4. This chapter provides a road map for the following chapters.

3.1 Motivation and Design Challenges

To motivate our research, we consider a scenario where a wireless sensor network is deployed to track the presence of a radioactive source and determine the effect of the presence of this radioactive source on the local environment. The user wants to gather information about the climatic conditions in that environment such as temperature, humidity, etc. Therefore, a human operator sends the following query to all nodes in the network: "What is the maximum temperature in a region where the radioactivity signal exceeds the threshold T". As a result, each sensor node that receives this query checks first if its reading related to the radioactivity signal exceeds the predetermined threshold *T*. If a node satisfies this condition it starts sending its temperature reading to the user. However, since wireless sensor networks are deployed densely and usually static, the propagation of the user query will result in a huge volume of data and waste of scarce resources. Therefore, communication mechanisms are needed to reduce this amount of data and deliver it to this user in an energy efficient manner. Moreover, the source might be mobile, and the user may want to track this source and gather the same environmental information while it is moving. This mobility adds more complexity to the communication in wireless sensor networks.

The energy efficiency is not the only challenge in the design for communication protocols for wireless sensor networks. In the case of wireless sensor and actor networks sensor nodes are deployed to track an event and inform actor nodes so they can perform a specific action. However, due to the density of sensor nodes, many sensor nodes may detect the same event at the same time and inform many actors where a single actor node is enough. Therefore, in addition to the energy consumption, the density of the sensor nodes adds a coordination issue to the communication in wireless sensor networks.

This section reviews the issues related to routing in wireless sensor networks that were raised in the previous chapter, and explains our choices. First, we will consider the problems related to routing algorithms in wireless sensor networks. Then, we will consider the problems related to routing in mobile event monitoring applications, and the coordination issue in wireless sensor and actor networks.

3.1.1 Routing in Wireless Sensor Networks

As discussed in chapter 2, from surveying the existing number of routing protocols proposed in the literature we found that major works on routing in wireless sensor networks fall in two main categories:

a) *Data centric routing*: In this approach a user sends a query through the network in order to find nodes within a specific event area. Once nodes that satisfy the user query are found, these nodes start sending their information to the user sink. This approach presents two main drawbacks:

- The query propagation operation used in this approach is based mainly on flooding. Knowing that wireless sensor networks suffer from resources constraints such as energy and bandwidth, such technique is highly costly and may threat the network connectivity and reduce its lifetime.

- Since wireless sensor nodes are densely deployed, the number of nodes that may reply following the user query propagation into the network is huge and may generate a huge amount of correlated data. However, although wireless sensor network are resources limited the proposed data centric approaches do not take into consideration this correlation to reduce the amount of data and scarce resources.

b) *Hierarchical clustering routing*: Unlike data centric routing, this approach considers the data correlation that characterizes wireless sensor networks, by organizing the sensor nodes into groups, where each group has a leader. This leader is responsible for gathering information from its group members, applying an aggregation operation on it and relaying the result to the sink. Although current routing protocols based on hierarchical clustering achieve good resources saving and extend the network lifetime, this approach has several drawbacks, the most important are:

- The factors used in the cluster formation process are mainly based on neighbouring and radio signal strength criteria. Unlike the data centric approach, hierarchical clustering do not take into consideration the user query and therefore it cannot be used in applications where the user is interested in gathering information about a specific event such as in target tracking.

- Since all cluster members send their data to the cluster head first, this operation represents a significant overload on the cluster head. In a dense network where clusters contain hundreds of nodes, the cluster-head will dissipate a great part of its energy in this operation, and thus a cluster-head re-election is needed.

From the mentioned issues, we can see the existing routing approaches are either not resources efficient or do not satisfy the user requirements. Therefore, it is necessary to define a new routing approach that can satisfy the user requirements, and considers the resources constraints of wireless sensor network.

3.1.2 Routing in Mobile Event Monitoring Applications

As described in chapter 2, we found in the literature many works that treat the problem of routing protocol in mobile event monitoring applications for wireless sensor networks. However most of these works fail to propose an energy efficient solution to the problem and few of them use the clustering technique as a routing approach [Chen'04, Fang'03]. Nevertheless, these clustering based protocols also present some drawbacks, the most important ones are:

- The existing work do not consider the energy constraint as a major issue since it assumes a heterogeneous wireless sensor networks that contain a number of highly capable sensor nodes that do not suffer from energy constraints. However, in many applications wireless sensor networks are composed of homogenous sensor nodes with limited energy reserves. Therefore, new energy efficient communication solutions for mobile event monitoring applications are needed.
- Many of the of target tracking applications are used to monitor physical events that occur in the nature. These events may split at a certain moment and generate new events with the same nature that need to be monitored as well. However, existing works do not consider this issue.

These issues emphasize the necessity for a new routing approach for event monitoring applications in wireless sensor networks. This new routing approach must be flexible enough to support the high mobility of tracked event and its different characteristics, while respecting the resources constraints of the wireless sensor network.

3.1.3 Data Dissemination in Wireless Sensor Networks

Following our literature review on routing protocols in wireless sensor networks presented in the chapter 2, we found that these protocols use either a single data dissemination approach or a multipath data dissemination approach. However, both approaches present some drawbacks that need to be addressed:

- *Single path approach*: This approach finds the best path according to a specific parameter related to the required performances, such as the distance between the source and the sink, the time delay, etc. Despite the low resource consumption and short delay achieved by this approach, it can not be used for long time data delivery as it concentrates the traffic on the same path for the whole transmission and may result in energy exhausted nodes and the loss of the network connectivity.

- *Multipath approach*: Unlike the single path dissemination, this approach establishes many paths between the source and the destination in order to guarantee a longer data dissemination and better network connectivity. While these two goals are achieved by the multipath approach, it results in much more energy consumption and duplicated data delivery.

The challenge here is to design a data dissemination scheme that can bring the advantages of both approaches. This data dissemination scheme will be more energy efficient than multipath approach, and more robust than single path approach.

3.1.4 Coordination in Wireless Sensor and Actor Networks

In the previous chapter we introduced wireless sensor and actor networks, we presented their advantages and how these networks are expected to work. We showed also that the automated mode with a single actor model is suitable for a large number of applications that use this kind of networks and clarified that there are not too much work on this area. Using the wireless sensor and actor network in automated modes raises the following issues:

- The lack of coordination between sensor nodes that detect an event in the study field, since each sensor node operates independently from any other node. Such lack of coordination may lead to the invocation of many actor nodes while a single actor is enough.

➢ The lack of coordination between sensor and actors, since sensor nodes are generally not aware about the position of actor nodes. In the situation where a sensor node detects an event, it may not find the nearest actor to the event area and may broadcast its data messages to the whole network, wasting scarce energy and bandwidth resources.

The mentioned coordination issues are important and need to be addressed. Therefore, it is necessary to design a coordination framework that helps to group sensor nodes that detect the same event and makes the communication between them possible. Such framework must also allow sensor and actor nodes to discover each other and provide a way of communication between them.

3.2 Semantic Clustering Mechanisms for Communication

Our solution to address the mentioned challenges is new communication protocols and mechanisms for wireless sensor networks based on semantic clustering. These mechanisms consist of four novel schemes that aim to support energy efficient and data-accurate communication for wireless sensor networks:

a) A new semantic clustering routing protocol for wireless sensor networks [Bouhafs'06-a]
b) A new mobile event monitoring protocol for wireless sensor networks [Bouhafs'06-c]
c) A Coordination framework for single actor model in wireless sensor and actor networks [Bouhafs'06-c]
d) A node recovery scheme for data dissemination in wireless sensor networks [Bouhafs'06-e]

In this section we describe these novel contributions in details

3.2.1 A Semantic Clustering Routing Protocol

We present a new semantic clustering routing protocol that allows sensor nodes within the same area and sharing the same semantic properties to work cooperatively. This collaboration aims to generate high level information to the user and avoid unnecessary transmissions using data gathering and aggregation means. This protocol has several advantages:

- Only nodes within a certain region of interest and satisfying user data requirements are grouped in a same cluster.

- The query dissemination scheme used in this protocol to find the sensor nodes within the region of interest avoids flooding and saves more energy.

- Cluster members are organized in form of tree and a layered data aggregation is performed along this tree until the cluster head. This layered data aggregation guarantees distributed energy dissipation among cluster members and avoids overload on the cluster head.

A complete description of this protocol is presented in chapter 4.

3.2.2 An Energy Efficient Clustering Protocol for Mobile Event Monitoring

We develop an energy efficient routing protocol for mobile event monitoring applications based on semantic clustering. The proposed protocol adapts our semantic clustering routing protocol so that it is able to deliver accurate data about a highly mobile event to the user at minimum cost. The main advantages of this protocol comparing to existing works are:

- The protocol uses a cluster membership update scheme that allows maintaining the cluster that contains the nodes detecting the mobile event. This scheme helps to deliver the required data about the monitored event, efficiently and continuously, while it is moving.

- A cluster split scheme that allows monitoring event split that may occur in the nature. This scheme helps to build clusters around the new resulting events and to deliver information about them to the user separately.

Details of this protocol are presented in chapter 5 of this thesis.

3.2.3 Node Recovery Scheme for Data Dissemination

We present a new node recovery scheme for data dissemination in wireless sensor networks. This scheme, could be used with any single path routing protocol, and allows replacing energy drained sensor nodes by new nodes that can take over the data forwarding procedure. The proposed node recovery scheme exploits the wireless sensor network density and the broadcasting nature of the wireless medium. The main advantages of this protocol are:

- It uses a single path data dissemination approach and hence involves less number of sensor nodes in the data delivery operation.
- It saves more energy than multipath data dissemination approach.
- It extends the routing path lifetime and offers a better network connectivity than single path approach.

In chapter 6, we will explain in more details how this node recovery scheme works, its benefits and which parameters affect its performances.

3.2.4 A Coordination Framework for Single Actor Model

We present a coordination framework for the single actor model in wireless sensor and actor networks. In this model, when an event is detected only one actor is required to deal with it and can eventually inform other actors. The proposed framework uses semantic clustering to group nodes within the event area and allows a collaborative election of the cluster head in order to inform the nearest actor to the event area. The main advantages of this protocol are:

- It satisfies the single model condition by informing only the nearest actor when an event is detected.
- It reduces the number of data messages generated by sensor nodes when an event is detected.
- It achieves reasonable delay between detecting an event and informing the nearest actor to it.

A complete description of this framework and its different phases is presented in chapter 7.

3.3 Simulation Environment

For even moderately sized networks with tens of nodes, it is impossible to analytically model the interactions between all the nodes. Therefore, simulation was used to determine the benefits of different protocols using the Georgia Tech Network Simulator (GTNetS) [Riley'03]. GTNetS is a network simulation environment designed specifically to allow large scale simulations. The different wireless sensor network models such as radio propagation model, computation and communication energy dissipation models were implemented in this simulator.

In the simulations described in this thesis we use the environmental and radio energy models presented in chapter 2, in section 2.9. For this model we use the parameters described in [Heinzelman'02], where the radio electronics energy E_{elec} is set to 50 nano Joule per bit, The radio transmitter energy for distances less than $d_{crossover}$, $l_{friss-amp}$ is set to 10 pica Joule per bit per m^2, and the radio transmitter energy for distances greater of equal to $d_{crossover}$, $l_{ray-two-amp}$ is set to 0.0013 pica Joule per bit per m^4. In our simulation, we assume that sensor nodes use the IEEE 802.15.4 [Howit'03] standard. Therefore, we set their radio range to 15 meters and the distance threshold, for which the free space model is used, $d_{crossover}$ to 10 meters. The initial energy for each sensor node is set to 2 Joule. All these parameters are summarized in table 3-1.

Node initial energy	2 Joule
$d_{crossover}$	10 m
E_{elec}	50 nano J/bit
$l_{friss-amp}$	10 pica J/bit/m^2
$l_{ray-two-amp}$	0.0013 pica J/bit/m4
Radio Range	15 m

Table 3-1: Simulations parameters

3.4 Summary

In this chapter we described our proposed semantic clustering mechanisms for communication in wireless sensor networks. Since wireless sensor networks are characterized by harsh resources constraints it is obvious that the communication protocols must be resources efficient. Among all the proposed approaches to solve the resources problem in wireless sensor networks, clustering seems to be the best choice. However, this choice is not driven by these constraints only, the distributed nature of wireless sensor networks and their density make clustering the most efficient approach to implement.

In addition to resource constraints, the communication protocols must provide a highly descriptive and accurate information to the user. For our work, we clearly define the challenges that need to be considered in order to achieve both high level description information and efficient resources consumption.

First, a routing protocol needs to be designed using semantic clustering in order to allow a high data aggregation and minimum number of transmissions. This routing protocol must consider the data similarity between sensor nodes as the main criterion to build clusters in order to achieve high data accuracy.

Second, as the user may be interested in gathering information about a mobile event, a routing protocol that support mobility is needed. This routing protocol must allow the monitoring of mobile events and the gathering of information required by the user continuously, while considering the wireless sensor network constraints.

To make the proposed mechanisms robust against energy exhaustion of sensor nodes and in order to extend the network lifetime, robust and resources efficient data dissemination solution must be used to deliver data to the user and save the network connectivity at the same time.

Finally, the design of a coordination framework in wireless sensor and actor networks needs to be considered. This coordination framework must allow informing the nearest actor node only when an event is detected and minimize both the energy consumption and the time delay.

We present briefly the novel aspects of our communication mechanisms and we give an overview on their roles and advantages. In the following chapters we will explain with more details these novel contributions and evaluate them.

4 A Semantic Clustering Routing Protocol

Wireless sensor networks are expected to enable reliable monitoring of remote areas. These networks are essentially data gathering networks where the user is interested in high-level description of the environment the sensor network is monitoring. As described in the previous, in our work we consider wireless sensor networks applications where the user is interest in tracking and gathering information about a specific event that is source of signal as it is the case in radioactive wireless sensor networks [Brennan'05, Cerpa'01, Nemzek'04, Stephens'04].

For instance, the user may broadcast the following query: "What is the maximum temperature in a region where a radioactive object is exceeding the threshold T". As a result, each sensor receiving this query checks first if its readings related to the radioactivity satisfy the user query, before it starts collecting information about the temperature. Once individual nodes meeting the radioactivity condition receive the query, they start sending their temperature readings to the user. As wireless sensor networks are densely deployed, many nodes within the area of interest i.e. the area where the signal exceed the specified threshold will reply to the user query, which will result in a huge volume of correlated data and waste of resources. The challenge is to design a communication solution that allows the user to query these specific nodes while consuming less resource.

We address this challenge by proposing a semantic clustering protocol that involves only nodes that are relevant to a given query or task, and groups them in a cluster. This offers a possibility to minimize the communication energy cost and the data amount through local collaboration and data aggregation. Unlike existing clustering schemes where neighbouring information is the only parameter considered in the cluster formation, in this work semantic relevancy to a user query or task is also considered while forming the cluster.

This chapter is organized as follows: Section 4.1 will review the major communications techniques found in the literature, and will outline theirs drawbacks. Section 4.2 will give an overview on our semantic clustering protocol and describe its different phases. In section 4.3 we will evaluate our protocol analytically while in section 4-4 we will evaluate it by simulations. Finally, in section 4-5 we will present a summary of this chapter.

4.1 Background

As described in chapter 2 several routing approaches for wireless sensor networks have been proposed in the past few years. The major part of these approaches falls in one of two main categories: Data-centric routing, and Hierarchical clustering routing, while there are few other routing approaches based on sensor nodes location, network flow or quality of service (QoS) awareness.

Directed diffusion [Intanagonwiwat'00, Intanagonwiwat'03] is one of the first data-centric routing protocols for long-lived continuous queries. In this scheme, a user interest for some data is initially distributed through the network via flooding to find the sources of the relevant data. Once found, the source nodes start sending data to the sink along the paths created by the interest propagation process. The work presented in [Heidemann'01] aimed to adapt directed diffusion to specific applications. Many other protocols have been proposed either based on Directed Diffusion or following a similar concept [Braginsky'02, Sadagopan'03, Schurgers'01, Yao'02]. Although direct diffusion results in high quality paths, its flooding query dissemination technique is highly costly in terms of both energy and bandwidth. Other data-centric routing protocols have been proposed based on information gradient [Chu'02, Liu'03, Ye'05], where a proactive phase is used to prepare gradient information repository towards the tracked event. However, the well established physics laws that drive the physical events are not considered while preparing the gradient information repository, which can lead to the creation of unlimited number of paths and result in wasting of scarce resources. Recent works have been proposed based on the same idea and using event's finger prints as gradient information to establish a path toward event area [Faruque'03, Faruque'04, Henderson'04]. Although these data-centric protocols solve the problem of query dissemination, the authors did not propose any solution for data correlation and energy efficient routing problems.

Hierarchical clustering routing approaches aim at maintaining the energy consumption of sensor nodes by involving them in multi-hop communication within a particular cluster. Cluster formation is based, generally, on the energy reserve of sensors and sensor's proximity to the cluster head [Buczak'98, Lin'97]. The protocol LEACH developed in [Heinzelman'00, Heinzelman'02] is one of most popular clustering algorithms in sensor networks. The idea proposed in this work is to form clusters of sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. Data aggregation and fusion are local to the cluster. This will save energy since the transmissions will only be done by cluster heads rather than all sensor nodes. Cluster heads change randomly over time in order to balance the energy dissipation of nodes. This idea has been an inspiration for many hierarchical routing protocols [Lindsey'03, Manjeshwar'01, Manjeshwar'02]. Although clustering technique is an efficient routing technique to save energy, it considers only neighbouring and energy reserves information when forming clusters without taking into consideration the relevancy of cluster members to a user query or a tracked event, which makes it not suitable for event monitoring and continuous query applications.

In this work we propose a different routing approach for wireless sensor networks based on semantic clustering. Instead of grouping nodes according to their neighbouring properties only, in this approach we consider also the semantic properties of the sensed data in the clustering operation. The proposed routing protocol allows to group nodes relevant to a user query in the same cluster in order to achieve both data accuracy and resources saving.

4.2 Semantic Clustering Routing Protocol

Physical events occurring in the nature can be either static or mobile. In this section we consider the static event case only and we develop a new clustering protocol that group sensor nodes within the event area in the same cluster. The main idea of the clustering scheme proposed in this work is to group sensor nodes in clusters such as the clustering policy considers both semantic information and connectivity properties.

A user query is disseminated through the sensor network looking for a specific group of sensor nodes. Upon the query reaches a node satisfying the query, this node will elect itself as cluster-head and start forming a cluster that contains all nodes in its region satisfying the same query. In each cluster, nodes form a tree where the cluster head is the root. Data travelling from leaf nodes towards the cluster head are aggregated at each parent node through the tree in order to reduce the amount of redundant data. The semantic protocol proposed in this work consists of three phases: interest propagation, cluster formation, and data dissemination. We also propose a filtering scheme that helps to determine erroneous reading nodes while establishing a path towards the event area.

4.2.1 Interest Propagation Phase

The interest propagation calls for a technique to reach the nodes which can detect the event with a certain threshold. Despite its simplicity, interest flooding can not be an efficient solution due to its cost in term of energy and bandwidth. Following the environmental model presented in chapter 2, the signal detected by a sensor node is inversely proportional to its distance from the source of the signal. Therefore, it is possible to find a path towards the event's source by setting a gradient to the nodes with the highest readings among neighbour nodes. However, this solution can not be applied to those nodes which are far away from the source and flooding is the only way to propagate the query to event area.

The interest propagation approach proposed in this work combines flooding to information gradient-based query dissemination approach. Initially, a query message is injected from the sink into the network. The query contains the event description field, the requested information field, and the sender node related information fields which contains the sender ID, its local reading, and the number of hops to the sink which is incremented by each node receiving the query. The local reading field is set initially to zero by the sink and it is changed at each node in the path towards the event. The interest propagation procedure follows one of the two following modes: Interest flooding or greedy forwarding.

A. Interest Flooding Mode

A node receiving the query checks if it can satisfy the query or not by comparing its reading to the event description. If the receiving node can satisfy the query it enters in a cluster formation phase otherwise it compares its reading to the sender reading. If the node finds that its reading is greater than the sender reading it starts a gradient set-up operation, otherwise it broadcasts the query to its neighbours. Figure 4-1 illustrates the interest propagation by flooding.

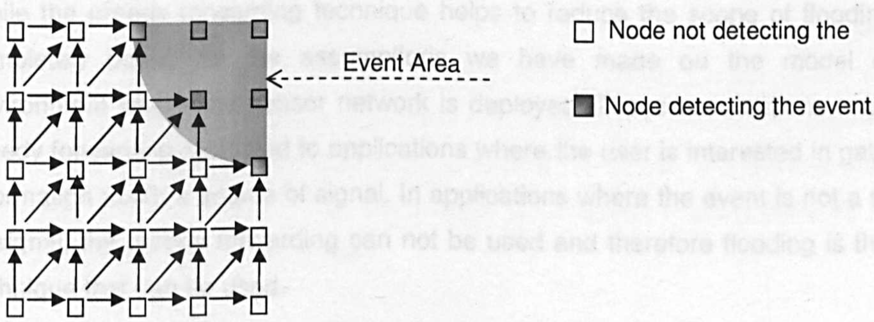


Figure 4-1: Interest flooding mode

B. Greedy Forwarding Mode

If a sensor node finds that the signal starts increasing it enters this mode, otherwise it stays in the flooding mode. In this mode, a node finds a path towards the event area by looking for the neighbouring node with the highest reading. Each node sends a data request to its neighbours; after the neighbours reply, the sender node chooses the neighbouring node with the highest reading as *next hop node* and forwards the query to it. Figure 4-2 illustrates the interest propagation by greedy forwarding.

The greedy forwarding stops when eventually the event area is found. Note that in both algorithms interest forwarding and greedy forwarding, each node updates the hops counter.

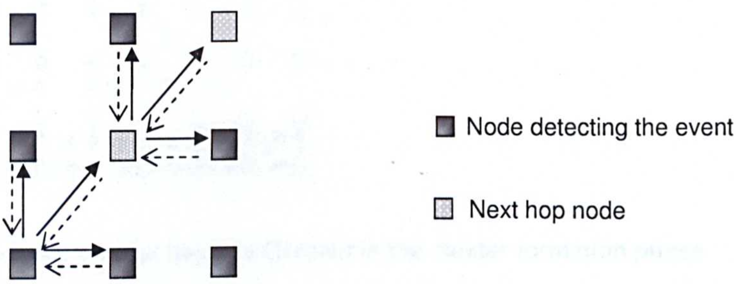


Figure 4-2: Interest forwarding

Discussion:

While the greedy forwarding technique helps to reduce the scope of flooding it is completely based on the assumptions we have made on the model of the environment where the sensor network is deployed. These assumptions make the greedy forwarding restricted to applications where the user is interested in gathering information about a source of signal. In applications where the event is not a source of signal, the greedy forwarding can not be used and therefore flooding is the only technique that can be used.

4.2.2 Cluster Formation Phase

The cluster formation is normally initiated by the first node within the event area receiving the interest message, which would be the cluster head. However, as we use a multi-path interest propagation approach it is more likely that many nodes within the event area receive the query message at almost the same time as illustrated in figure 4-3, which results in many cluster head candidates. Therefore, a cluster head election criterion needs to be defined.

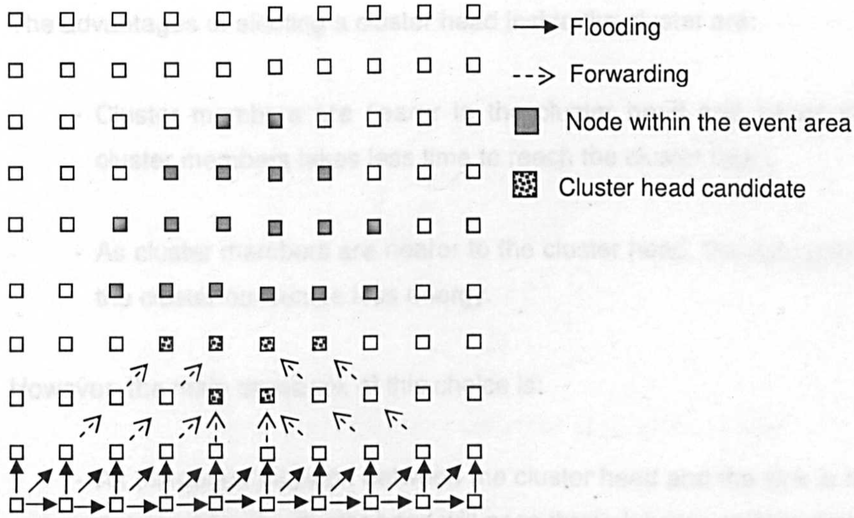


Figure 4-3: Cluster head candidates in the cluster formation phase

Cluster Head Election Criterion

In the case of a heterogeneous wireless sensor network where sensor nodes have different energy reserves, a sensor node with highest energy reserve is usually elected as cluster head [Heinzelman'02] so the lifetime of the cluster is extended. However, in our work we consider a homogenous wireless sensor network where sensor nodes have the same energy reserves. In this case, the cluster head election must follow another criterion that helps to extend the cluster lifetime and therefore, the position of the node within the cluster is considered rather than its energy reserve. We can define two cases:

- Cluster head inside the cluster as it is illustrated in figure 4-4.

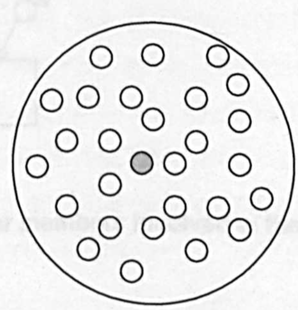


Figure 4-4: Cluster head inside the cluster

The advantages of electing a cluster head inside the cluster are:

- Cluster members are nearer to the cluster head and hence data sent by cluster members takes less time to reach the cluster head.

- As cluster members are nearer to the cluster head, the data gathering inside the cluster consumes less energy.

However, the main drawback of this choice is:

- As the communication between the cluster head and the sink is multihop, the data sent by the cluster head will pass through some cluster members as it is illustrated in figure 4-5. Knowing that these cluster members send their own data periodically to the cluster head, this will increase the burden on these nodes. If these cluster members die the cluster head will not be able to send the aggregated data to the sink.

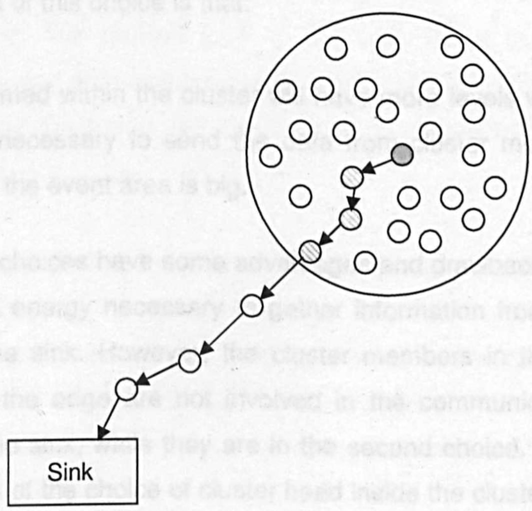


Figure 4-5: Cluster members involved in the data dissemination

- Cluster head at the edge of the cluster as it is illustrated in figure 4-6.

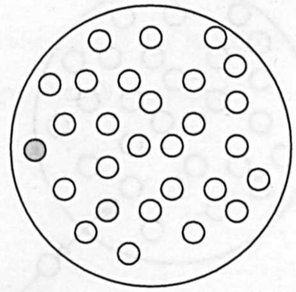


Figure 4-6: Cluster head at the edge of the cluster

The advantage of electing a cluster head at the edge of the cluster is that:

- Among the cluster head candidates at the edge of the event area it is possible to find the nearest node to the sink and hence reduce the time delay and energy consumption necessary to send the data to the sink. Moreover, it avoids involving other cluster members in this data delivery

The main drawback of this choice is that:

- The tree formed within the cluster will have more levels which increases the time delay necessary to send the data from cluster members to the sink, especially if the event area is big.

It is clear that both choices have some advantages and drawbacks related mainly to the time delay and energy necessary to gather information from cluster members and deliver it to the sink. However, the cluster members in the case where the cluster head is at the edge are not involved in the communication between the cluster head and the sink, while they are in the second choice. This represents an important drawback of the choice of cluster head inside the cluster. Therefore, in the following we consider the case where the cluster head is at the edge of the cluster and is the nearest possible to the sink as it is illustrated in figure 4-7. This choice is used as cluster head criterion in our protocol.

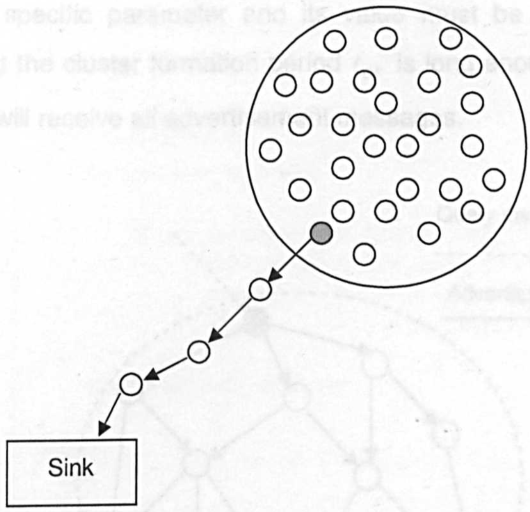


Figure 4-7: Cluster head election criterion

Cluster Head Election and Cluster Formation

As mentioned in the previous section, in our protocol, the cluster head election criterion is based on the shortest path to the sink. Since the interest message contains a *hops-counter* field which is incremented by each node receiving it either by flooding or greedy forwarding, the cluster head candidate with the less number of hops will be elected.

At first stage, each cluster head candidate broadcasts an advertisement message to its neighbours containing the query message, its *path length* towards the sink (number of hops) and message type field that indicates the type of the message. Note that the number of hops is used by the nodes within the event area as a parameter to elect a cluster head, and it will not be incremented in this phase.

At second stage, each neighbour node that receives an advertisement message for the first time, checks first if it is within the area of the described event. If the receiving node is within the event area it considers the sender as its parent node, saves the *path length* field and the *cluster head candidate id*, and enters a cluster formation phase for a period of time t_{CF}. A node which is not within the event area and receives the advertisement message will simply ignore it. Note that t_{CF} is an application specific parameter and its value must be defined by the user. We assume that the cluster formation period t_{CF} is long enough so all nodes within the event area will receive all advertisement messages.

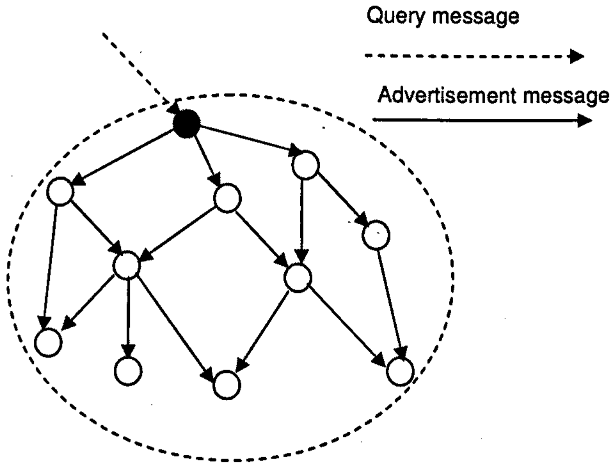


Figure 4-8: Example of cluster formation

A node within the event area that receives another advertisement message before the cluster formation time t_{CF} expires would compare the advertisement *path length* field with the previously saved *path length.* If the new *path length* is less than the saved *path length,* the *parent node id* is replaced by the new advertisement message *sender id.* The algorithm used by nodes within event area to elect cluster head is described in figure 4-9.

Note that this procedure is performed by all nodes within the event area including cluster head candidates.

```
Receive adv_message;
path_length= adv_message.path_length;
parent_id  = adv_message.sender_id;
ch_id      = adv_message.ch_id;
Set Timer t_CF ;
Until t_CH expires do
    Receive adv_message;

        If adv_message.path_length<path_length
            path_length= adv_message.path_length;
            parent_id  = adv_message.sender_id;
            ch_id      = adv_message.ch_id;

    Broadcast adv_message;

End do
```

Figure 4-9: Cluster head election algorithm

At the end of the cluster formation period all the nodes will have the same *cluster head's id*, each node will have one parent node to which it sends a join message as it is illustrated in figure 4-10. This message contains the node's id, the *cluster-head's id* and a header that indicates the type of the message. The cluster formation results in a semantic tree where each node has a single parent, and where the elected cluster head is the root of the tree.

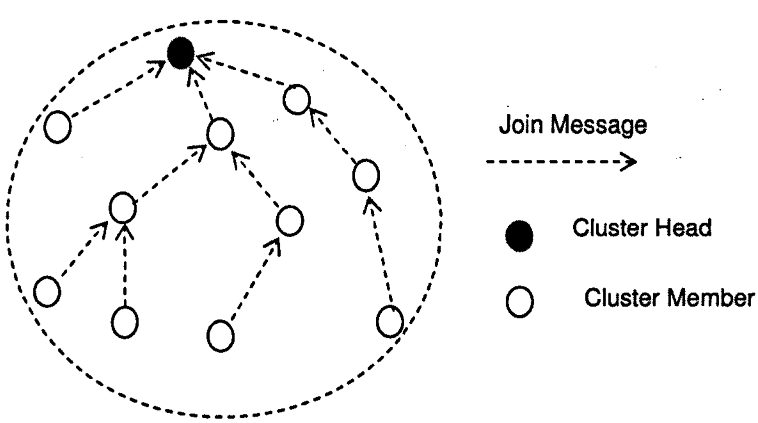


Figure 4-10: Example of tree formation

4.2.3 Data Dissemination Phase

This phase can be considered as the final stage in this clustering scheme and it is initiated by the tree leaf nodes within the cluster. Each leaf node gathers the data requested in the query message and pushes it towards its parent in the tree. Each parent node set a timer $t_{gathering}$ and waits to receive data from its children nodes. Once the timer expires, each parent node applies an aggregation operator on the received data and its own data, and then forwards it to its parent. We assume that the communication between cluster members is synchronized and that the value of $t_{gathering}$ is long enough to allow each parent to receive data from its children nodes.

When the cluster-head receives all aggregated data, it applies its aggregation operator on it and sends the result towards the sink following a reverse path routing. As the minimum number of hops is used as criteria for the cluster head election algorithm, the reverse path between the cluster head and the sink is the shortest path to disseminate the data to the user.

4.2.4 Case of Multiple Queries

Although we considered only the case of a single query it is possible that applications send multiple queries simultaneously into the network.

As mentioned earlier in this chapter, the user query generally defines an area of interest where a specific source of signal is detected. This query describes also the type of information that the user wants to gather. Therefore, in the cases of multiple queries the user may define different areas of interest and different type of information. For the sake of simplicity, we consider the case of two queries.

As the two queries propagated into the network define two areas of interest, we can the three following possibilities:

1. *The two areas are totally separated from each other.* This correspond to the scenario where the two queries describe two totally different areas and the user wants to gather specific information from sensor nodes within each area.

2. *The two areas overlap partially*: This correspond to the scenario where the user queries describe two areas of interest that partially overlap.

3. *The two areas overlap totally*: This case correspond to the scenario where the user is interest in gathering two different types of information from the same area. For instance, the user might send a first query to gather temperature information and the second query to gather humidity information from the same area.

We will study how our protocol progress according to these three cases.

Interest Propagation:

- *The two areas are totally separated from each other*: In this case the two queries propagate into the network following the two modes flooding and greedy forwarding. In the greedy forwarding mode each query builds its own paths, and there will be no common paths.

- *The two areas overlap partially*: In this case the two queries propagate into the network in the same way as described in the previous case. However, unlike the previous case, some paths created in the greedy forwarding mode by the two queries will be common. In other words some sensor nodes will be involved in the greedy forwarding for both queries.

- *The two areas overlap totally*: Like the two previous cases, the queries will propagate into the network following the two modes: flooding and greedy forwarding. However, in this case these queries will share the same paths towards the same event area.

Cluster Formation and Data Dissemination:

- *The two areas are totally separated from each other*: Clusters are formed around the two event areas, cluster heads are elected, and the sink starts receiving data from the two cluster heads. The only extra cost in this case in comparison with the case of a single query is the energy consumption.

- *The two areas overlap partially:* Cluster formed around the two areas will overlap resulting in common cluster members. Such situation adds more complexity to our protocol as some sensor nodes will be cluster members in two different trees and will have two parents as it is illustrated in figure 4-11.

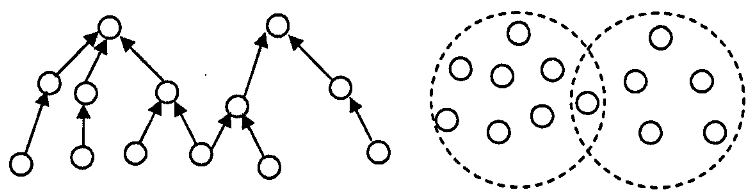


Figure 4-11: Partial Overlapping

A solution to this problem is to associate a query id to each query. In this case, a cluster member will need to associate a query id with its parent id. Common cluster members will have also more burden than the other cluster members and will be exposed to early death especially if they have children nodes from both clusters. This will result in the loss of parts of both clusters and a part of the data gathered inside each cluster. The importance of the cluster members and data that will be lost in this case depends on how much the two event areas overlap.

- *The two areas overlap totally:* In this case, sensor nodes that satisfy the two queries will be grouped in the same cluster and the same tree will be built. To differentiate the data, each node associates the query id with the data it sends to its parent node. When a parent node receives data from its children it checks first to which query the data corresponds before aggregating with it own data and sending the aggregate to the upper layer. This double data dissemination process will add more burden on all cluster members and further decrease the cluster lifetime.

Discussion:

Although we studied the case of two queries only, it is clear that the case of multiple queries adds more burden and complexity to our protocol, and the following conclusions can be made:

- An id needs to be associated with each query, so all the queries can be identified.
- Each cluster member needs to associate a query id with its parent id in the tree. This will allow a node to find out to which parent it should send the data.
- Sensor nodes replying to multiple queries will deplete their energy quicker than other nodes that reply to a single query.

In the rest of this chapter we will study the performance of our work for the case of a single query only.

4.2.5 Filtering Scheme

The main drawback of the greedy forwarding mode described in section 4.2.1 is its sensitivity to erroneous sensors reading. Indeed, as some sensors may have erroneous readings, the greedy forwarding algorithm may not find the event area and the source of the signal. To overcome this problem, it is necessary to apply a filter on the neighbours' readings before choosing the *next hop node*.

Recall that our work targets applications where the user is interested in tracking a source of signal such as a radioactive source and gathering information about it, and where the tracked signal propagates following the model presented in section 2.8. Therefore, we assume that the signal if a node is *i* within the vicinity of the source, the signal detected by the this node is:

$$n_i = n_0 e^{-\frac{d_i}{D}} \qquad (4\text{-}1)$$

Where d_i is the distance between the source and the node *i*, n_0 is the signal at the source, and D is a parameter specific to the nature of the signal and assumed to be already know as already explained in section 2.8.

Therefore, if a node *j* replies to a data requests coming from a node *i* and the signal detected by *j* is higher than the signal detected by i, the signal can be calculated as following:

$$n_j = n_0 e^{-\frac{d_j}{D}} \qquad (4\text{-}2)$$

Where d_i and d_j are the distances separating respectively node i and node j from the signal source, and $d_j < d_i$.

As the distance between the two nodes can not exceed the radio range R, we can deduct the following condition:

$$n_0 e^{-\frac{d_j}{D}} \leq n_0 e^{-\frac{(d_i - R)}{D}} \Rightarrow n_0 e^{-\frac{d_j}{D}} \leq n_0 e^{-\frac{d_i}{D}} \times e^{\frac{R}{D}} \qquad (4\text{-}3)$$

By replacing $e^{\frac{R}{D}}$ by a constant C, the condition (4-3) becomes:

$$n_j \leq n_i \times C \qquad (4\text{-}4)$$

By applying the condition (4-4) on each received reading in the greedy forwarding mode, it is possible to detect any erroneous reading, and choose the right *next hop node* as following:

Assuming that a node *i* receives data replies from two neighbours: *j* and *k* such as: $n_i > n_j > n_k$ where: n_i, n_j, n_k are the readings respectively of the nodes: *i, j, k*.

If $n_j > n_i \times C$ and $n_k \leq n_i \times C$ then node's *j* reading will be considered as erroneous and node *k* will be chosen as the *next hop node*.

This filter will be carried out by a simple check of the condition (4-4) at each node in the greedy forwarding mode.

While our proposed filtering is very simple and related to our routing protocol, there are some works that investigate the problem of erroneous readings in wireless sensor networks more deeply [Bhaskar'04, Luo'2006].

4.3 Discussion

While the user query is important to establish a path towards the event area, clustering and data aggregation are key parameters to our semantic clustering mechanisms performances. By analysing the proposed clustering protocol we can see that:

- The information-gradient based routing algorithm used in the interest propagation phase reduces the scope of flooding and thus achieves more energy saving.

- The data aggregation performed at each layer in the semantic reduces the amount of redundant messages and energy consumption.

- The tree organization within a cluster provides better energy consumption distribution between cluster members.

- The greedy forwarding algorithm used in the query dissemination, the cluster formation procedure, and the semantic tree organization, may add delay and complexity to the proposed protocol.

All these analytical results will be verified and investigated in more details in the following section.

4.4 Evaluation

In these simulations, our semantic clustering routing protocol is compared with Directed Diffusion and LEACH protocols. This comparison is in terms of network lifetime, energy dissipation, and time delay. In these simulations we use the simulations environment and parameters described in chapter 3. We set the query packet size to 39 bytes and the data packets size to 525 bytes. Our goals through these simulations are:

- Evaluate the performances of the interest propagation and cluster formation approaches in terms of energy consumption and time delay.

- Evaluate the efficiency of the filtering scheme against erroneous readings.

- Evaluate the performance of the data dissemination phase in terms of energy dissipation and load balance.

4.4.1 Evaluation of the Query Dissemination Scheme

In this section we evaluate our query dissemination scheme in terms of time delay and energy consumption by comparing it with the query dissemination used in Directed Diffusion.

For that, we simulate a wireless sensor network of 400 nodes uniformly deployed, where the distance separating each two nodes is 10 meters. In these experiments we simulate an event in the study field, where the event area radius is 50 meters.

The sink injects an interest into the network to find nodes within the event area. We place the event source at different positions in the network area and we measure for each experiment the total network energy consumed and the average delay for the query to reach the event area. The obtained results are presented in table 4-3 and table 4-4.

Distance (meter)	Energy consumed with Directed Diffusion (mJoule)	Energy consumed with Semantic Clustering (mJoule)
70.71	400	21×10^{-2}
141.142	400	23
212.132	400	120

Table 4-1: Total network energy consumption in the query dissemination

Distance (meter)	Delay with Directed Diffusion (ms)	Delay with Semantic Clustering (ms)
70.71	5×10^{-4}	5×10^{-4}
141.142	4×10^{-3}	13×10^{-2}
212.132	13×10^{-3}	32×10^{-2}

Table 4-2: Average delay to reach the event area

Figure 4-12 shows the total network energy consumption, in function of the distance between the sink and the event source for both Directed Diffusion and our semantic clustering protocol.

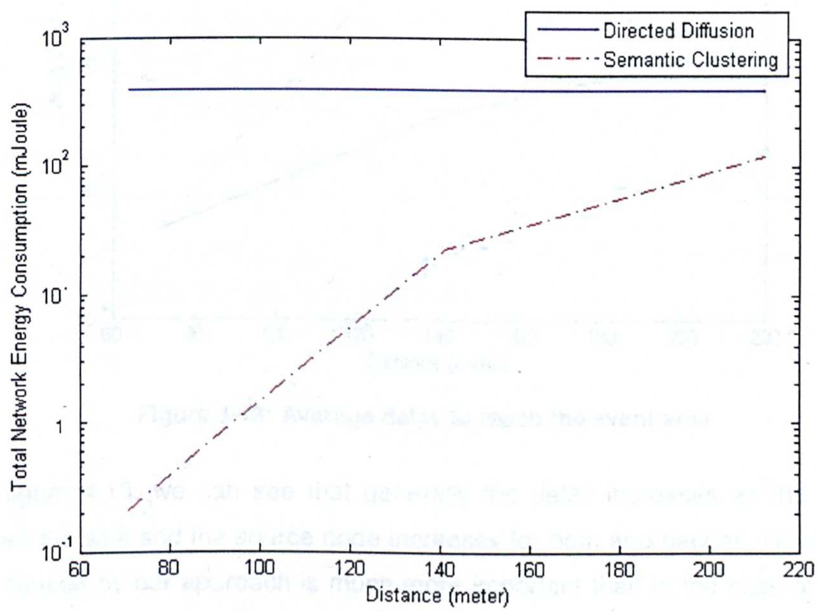


Figure 4-12: Total network energy dissipation in function of the network size

As shown in figure 4-12, using our semantic clustering protocol, the network energy consumption increases as the distance between the sink and the event source increases. This figure shows also that the network energy consumption with Directed Diffusion is constant and is not affected by the change of the event source position. This is because Directed Diffusion uses flooding technique in the query dissemination, which is independent from the distance between the sink and the event source.

Figure 4-13 shows the average delay for the query to reach the event area in function of the distance between the sink and the event source for both Directed Diffusion and our semantic clustering protocol.

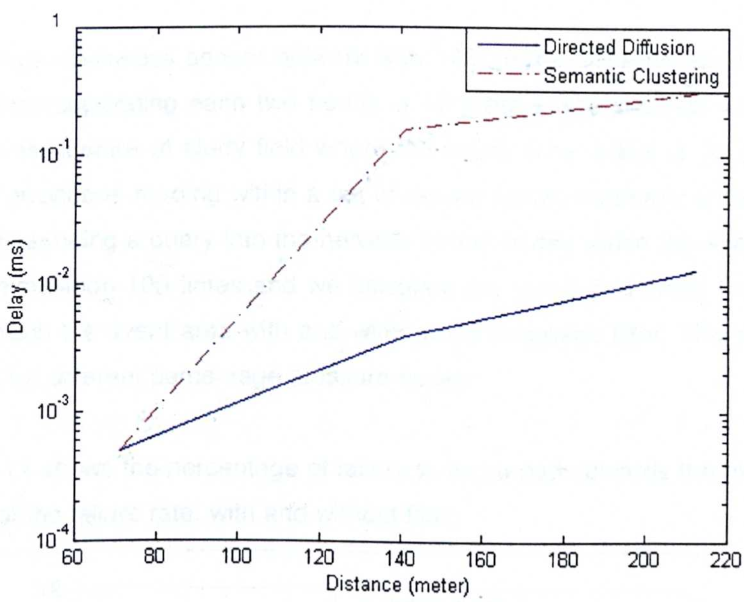


Figure 4-13: Average delay to reach the event area

From figure 4.13, we can see that generally the delay increases as the distance between the sink and the source node increases for both approaches. However, the delay caused by our approach is much more important than in the case of directed diffusion, especially when the area of interest is far away from the sink.

The obtained results show the trade offs between the delay to find the area of interest and the energy consumed in this operation for both approaches. With our approach we can not find the event area as fast as in the case of Directed Diffusion. In applications where the users is interested in gathering information about a specific event and where the energy is plenty, the delay exceed of our approach may not be acceptable and therefore Directed Diffusion is more suitable. However, in applications where the delay is not an important requirement and where the energy is scarce or queries are sent periodically into the network, our approach is a good candidate.

4.4.2 Evaluation of the Filtering Scheme

In this section we assess the efficiency of the proposed filtering scheme against erroneous reading. For that we evaluate the percentage failure for the query to reach the event area, with and without the filter.

We simulate a wireless sensor network with 100 nodes uniformly deployed, where the distance separating each two nodes is 10 meters. We simulate also an event source in the centre of study field where the event area radius is 50 meters. We simulate erroneous reading within a set of sensor nodes randomly chosen, and the sink starts sending a query into the network to find nodes within the event area. We run this simulation 100 times and we calculate the number of times that the query fails to reach the event area with and without the proposed filter. This simulation is repeated for different percentage of failure nodes.

Figure 4-14 shows the percentage of failure to find a path towards the event area, in function of the failure rate, with and without filter.

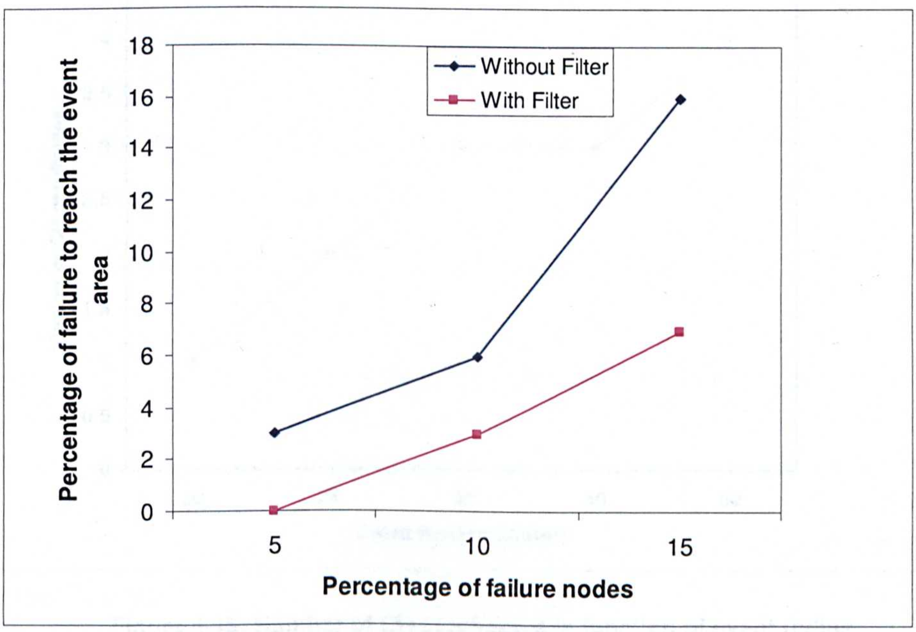


Figure 4-14: Percentage of failure to reach the event source

This figure shows that the percentage of failure of reaching the event area using the filtering scheme is less than without it. This figure shows also that as the percentage of failure nodes increases our filtering scheme becomes less efficient. Therefore, in applications where sensor nodes failure rate is relatively small (less than 10%) our filtering scheme might be effective. However, in applications where sensor nodes failure rate is important, this scheme can not be useful.

4.4.3 Cluster Formation Costs

In these experiments we want to evaluate the cost of the cluster formation phase in terms of time delay. For that we simulate 1000 nodes grid topology senor network and, an event in the centre of the study field. First, the sink injects a query looking for nodes within the event area, and we count the number of cluster head candidates and measure the time necessary to build a cluster. This time represent the time interval between the moment when the query reach the event area and the moment when the elected cluster head sends its first data packet towards the sink. We repeat this simulation for different event ranges. Figure 4-15 shows the number of cluster heads candidates in function of the event area radius.

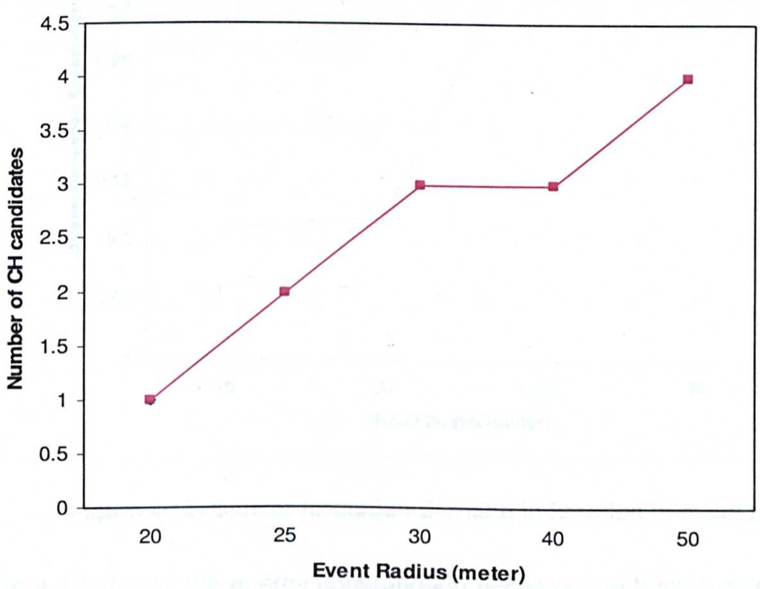


Figure 4-15: Number of CH candidates in function of event radius

This figure shows that the number of cluster head candidates increases as the event area radius increases. This is an expected result since an increase in the event area means that more nodes will cover the event area and hence more nodes contend to become cluster heads. This increase in the event radius has an impact also on the duration of the cluster formation process.

Figure 4.16 shows the time necessary to build a cluster for different event radiuses. shows that the time necessary to build a cluster increases generally with the event radius. It is worth noticing that these results are just to give an idea about how much time it takes to build a cluster according to our protocol. As the time necessary to build a cluster is in order of micro seconds it is hard to know how much time exactly the cluster formation process takes which explains why the measured delay is not increasing linearly. Therefore more accurate techniques are needed to measure this time delay.

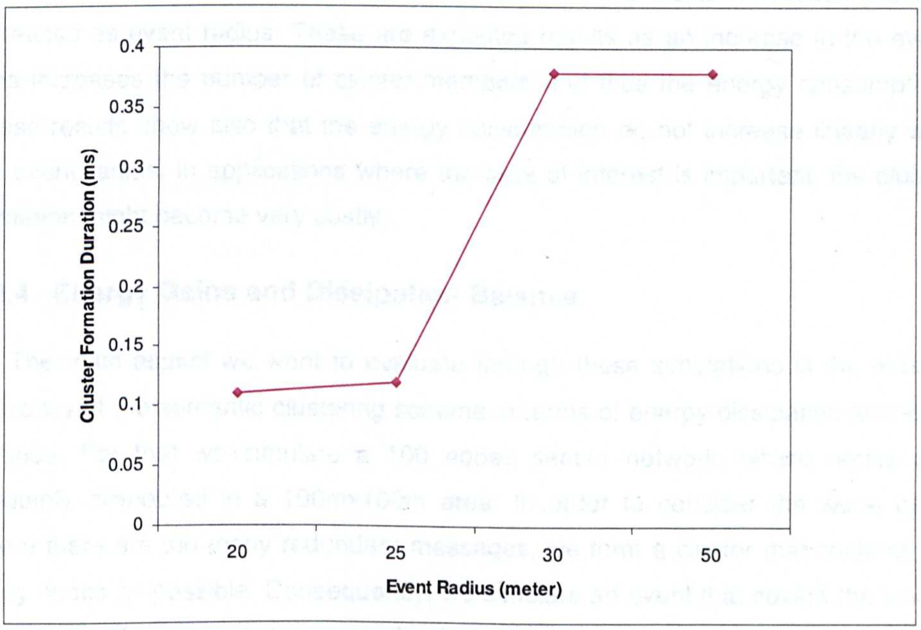


Figure 4-16: Cluster formation duration in function of event radius

Figure 4-17 shows, the energy consumption necessary to build a cluster for different event radiuses.

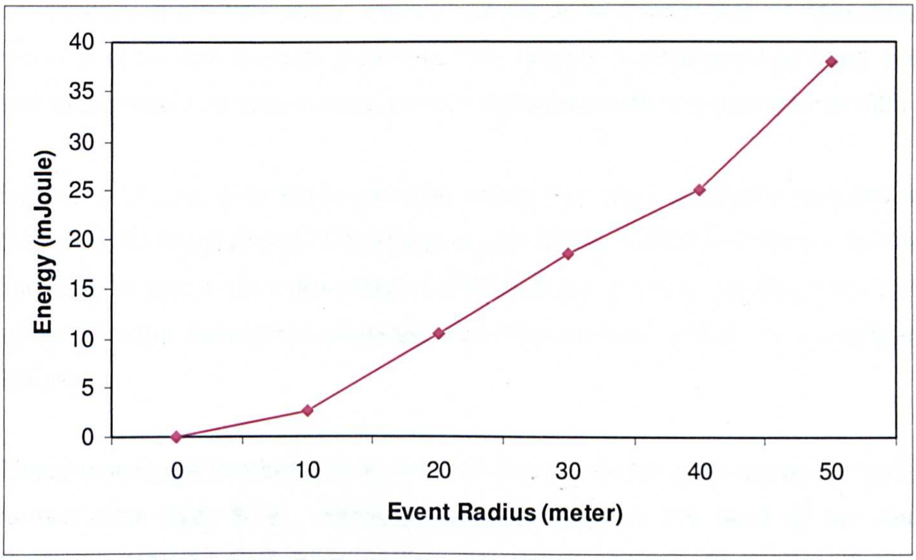


Figure 4-17: Energy consumption in the cluster formation function of event radius

Figure 4-17 shows that the energy consumption in the cluster formation process increases as event radius. These are expected results as an increase in the event area increases the number of cluster members and thus the energy consumption. These results show also that the energy consumption do not increase linearly with the event radius. In applications where the area of interest is important, the cluster formation might become very costly.

4.4.4 Energy Gains and Dissipation Balance

The main aspect we want to evaluate through these simulations is the energy efficiency of the semantic clustering scheme in terms of energy dissipation and load balance. For that we simulate a 100 nodes sensor network, where nodes are randomly distributed in a 100mx100m area. In order to consider the worst case where there are too many redundant messages, we form a cluster that contains as many nodes as possible. Consequently, we simulate an event that covers the whole study field. We compare our semantic clustering scheme to LEACH protocol which is a static clustering protocol. This choice is motivated by the fact that clustering protocols are aimed at reducing transmitted data using aggregation and thus saving more energy, which correspond exactly to the profile of our work.

To measure the total network lifetime we measure the number of data messages received at the sink for both protocols. The network is considered as dead when the sink stops receiving data messages from the sensor network [Heinzelman'02].

Figures 4-18 and 4-19 show the total number of data messages received at sink over time, for respectively LEACH and our semantic clustering protocol. As shown in figures 4-18 and 4-19, in the case of LEACH the sink stops receiving data after 630 sec, and in the case of our semantic clustering protocol it stops receiving data after 900 sec.

These results are confirmed in figure 4-20 that shows the total number of nodes that remain alive over time. Although, sensor nodes in the case of our semantic clustering protocol start dying earlier, the sensor network stays alive much longer than in the case of LEACH. The early sensor nodes deaths in the case of semantic clustering are due to the unfair distribution of the traffic among parent nodes in some parts of the tree, which leads to an overload on these parent nodes. However, the traffic in the rest of the tree remains fairly distributed and the energy dissipation as well.

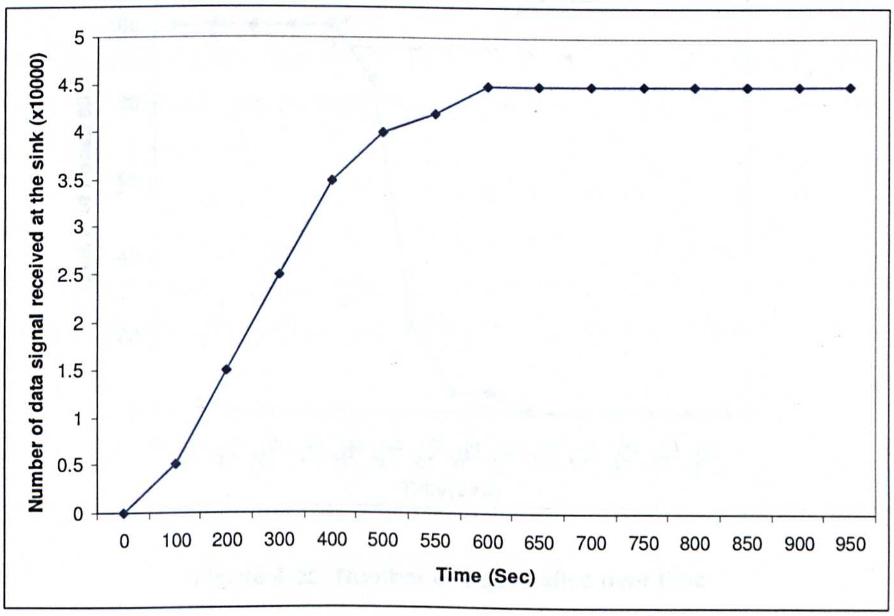


Figure 4-18: Number of data messages received at the sink with LEACH

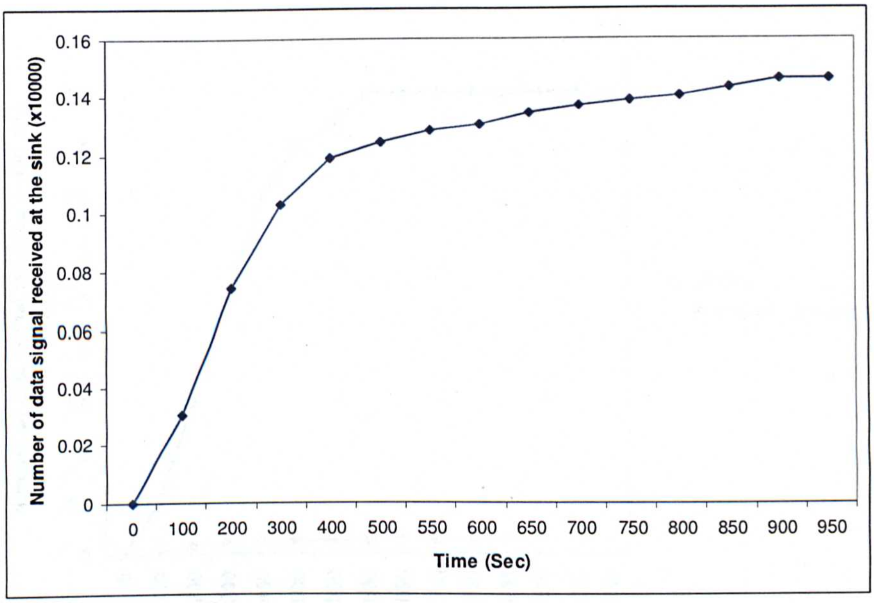


Figure 4-19: Number of data messages received at the sink Semantic Clustering

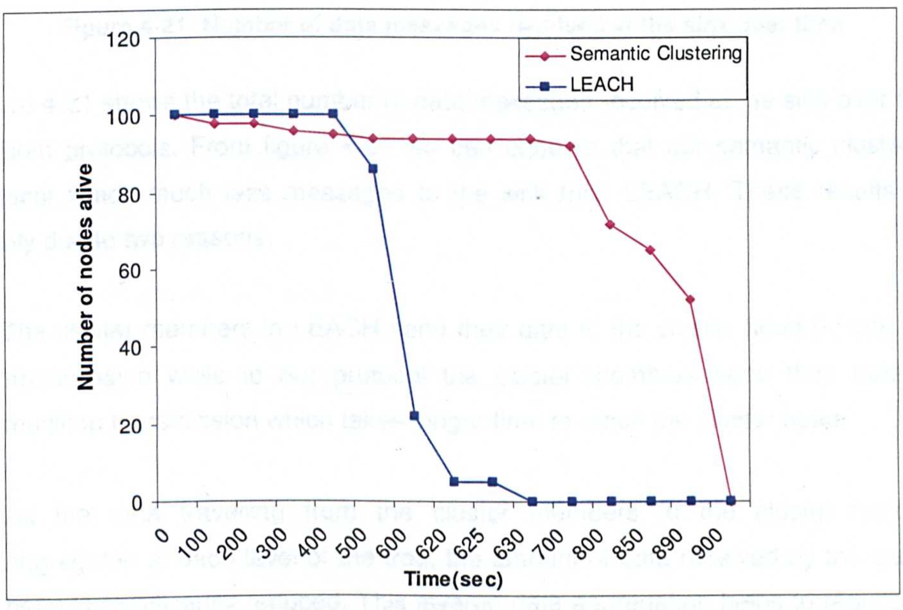


Figure 4-20: Number of nodes alive over time

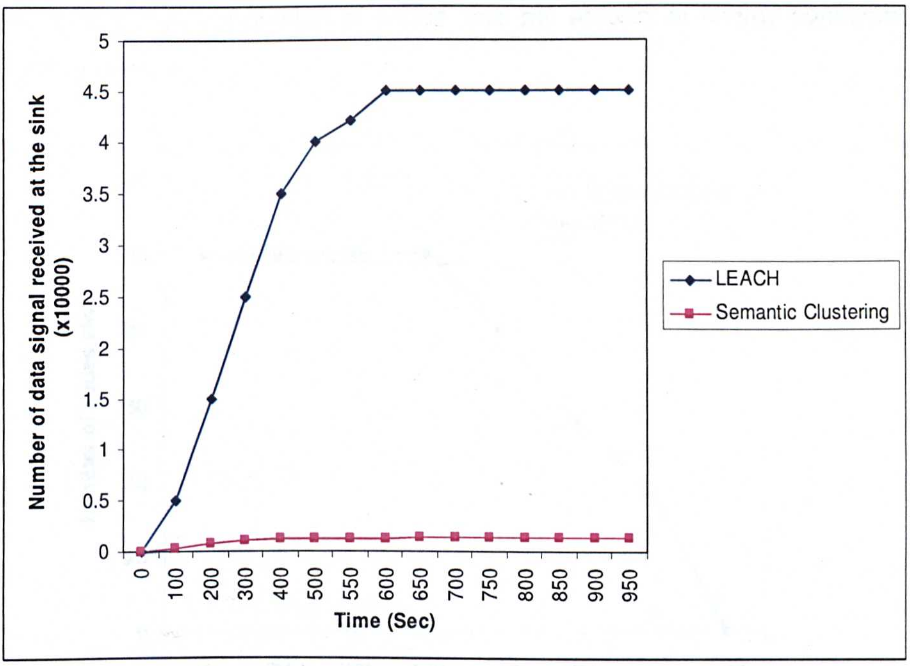


Figure 4-21: Number of data messages received at the sink over time

Figure 4-21 shows the total number of data messages received at the sink over time for both protocols. From figure 4-21 we can observe that our semantic clustering protocol sends much less messages to the sink than LEACH. These results are mainly due to two reasons:

1. The cluster members in LEACH send their data to the cluster head by one hop transmission while in our protocol the cluster members send their data by multihop transmission which takes longer time to reach the cluster head.

2. As the data travelling from the cluster members to the cluster head is aggregated at each level of the tree, the amount of data received by the cluster head is significantly reduced. This layered data aggregation helps to reduce the energy consumption and helps sensor nodes to stay alive much longer.

To compare the distribution of energy consumption in both protocols we measure the number of nodes alive as a function of the consumed energy in the network.

Figure 4-22 shows the number of nodes alive per amount of energy consumed by the overall network.

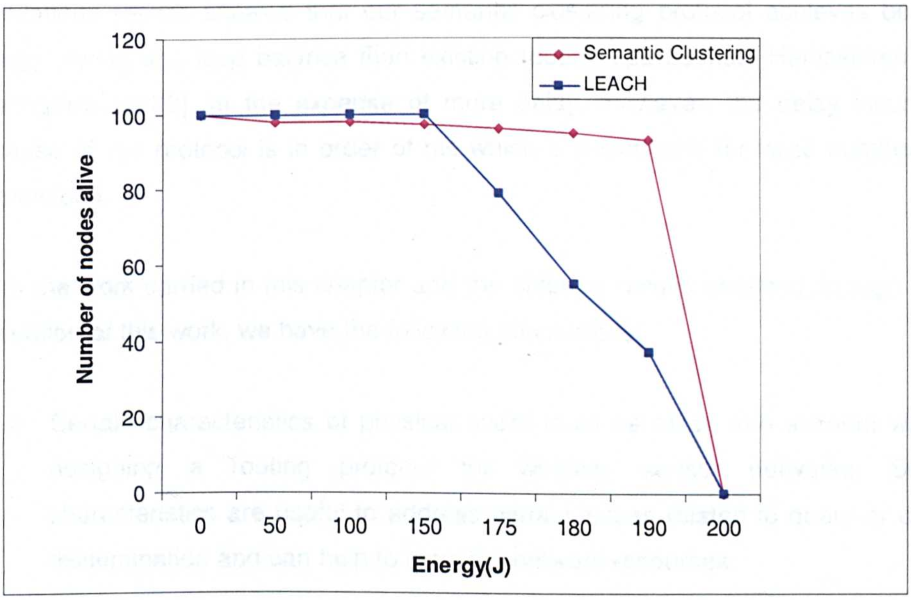


Figure 4-22: Number of nodes alive per amount of energy consumed

As shown in figure 4-22 our semantic clustering protocol achieves a better load balance than LEACH protocol. For example, when the energy dissipation in the semantic clustering protocol reaches 190 Joule which represent 95% of the initial network energy, 90 nodes (90% of the initial number) are still alive. However, with LEACH for same energy dissipation level only 35 nodes (35% of the initial number) are alive. These results indicate that our protocol achieves a better load balance among the cluster members, and thus, maintains the network lifetime much longer.

4.5 Summary

In this chapter we proposed a new resource efficient and application aware routing protocol for wireless sensor networks based on semantic clustering. In this protocol we developed a novel query dissemination scheme that uses established law of physics to find the event area for the user without flooding the whole network. We improved this query dissemination protocol by a filtering scheme against erroneous readings. We developed also a clustering scheme that considers relevancy of nodes to the user query in the cluster formation and organizes them in form of tree.

Simulations results showed that our semantic clustering protocol achieves better energy saving and load balance than existing routing approaches [Heinzelman'02, Intanagonwiwat'03], at the expense of more delay. However, the delay incurred because of our protocol is in order of ms which is acceptable for large number of applications.

From the work carried in this chapter and the different results obtained through the evaluation of this work, we have the following conclusions:

- Certain characteristics of physical event must be taken into account while designing a routing protocol for wireless sensor networks. Such characteristics are useful to address certain issues related to query or data dissemination and can help to save the network resources.

- Although clustering is an efficient approach to save the network resources, it is important to take into account the user requirements and consider the data accuracy as parameters in the clustering process. Once these parameters are taken into consideration, the clustering protocol can satisfy the user requirement and achieve good resource saving, and thus becomes an efficient protocol for the application.

- Grouping sensor nodes in clusters is an efficient approach to reduce the number of data messages and save the network resources, however; the performance of this approach can be improved by considering the organization of the sensor nodes within the cluster.

In the following chapter, we will consider the issue of mobile events in wireless sensor networks, by adapting our semantic clustering protocol to mobility. We will introduce a cluster membership update scheme that help to use our semantic clustering protocol to gather information about a mobile event in an energy efficient way. We will also present a cluster split scheme that allows the user to monitor an event split and gather information about the new resulting events.

5 An Energy Efficient Clustering Protocol for Mobile Event Monitoring

Habitat and environmental monitoring applications have the difficult task of gathering and communicating information continuously about specific events occurring in the environment. Wireless sensor networks are foreseen to become an efficient solution for many habitat and environmental monitoring applications. This kind of distributed sensing networks offers unique advantages over traditional centralized approaches. The intimate connection with its immediate physical environment allows each sensor node to provide localized measurements and detailed information that is hard to obtain through traditional instrumentation. However, in many of these applications, users might be interested in mobile events and need sensor nodes to send information continuously about the monitored event while it is moving.

For instance, if we consider the example presented in the previous chapter, where a user send the query: "What is the maximum temperature in a region where a radioactive object is exceeding the threshold T". According to our semantic clustering protocol presented in the previous chapter sensor nodes within the area of the radioactive source start collecting temperature information about the environment in a collaborative way by forming a cluster. However, in the case where the source is mobile (radioactive source carried in a car for instance), new issues raise. Indeed, as sensor nodes are usually static, cluster members' readings start decreasing as the radioactive source moves further away from its initial position.

Such situation may lead to change the cluster pattern or even destroy the cluster. New sensor nodes, on the other hand, start detecting the radioactivity signal when the radioactive source moves to a new position in the study field, and sending their readings to the user in unorganized manner, resulting in a burst of redundant data and waste of scarce bandwidth and energy resources. Moreover, the radioactive source may split into two or many sources which increases the numbers of sensor nodes involved in the communications with the user. Therefore, it is necessary to adapt the sensor nodes collaboration to mobility and maintain an organized monitoring of the mobile event.

We propose a new mobile event monitoring protocol based on semantic clustering protocol. Sensor nodes that detect the event's signal with a predetermined threshold are grouped in the same cluster using the semantic clustering protocol we have proposed in the chapter 4. The monitoring cluster is maintained by a cluster membership update scheme that allows sensor nodes to join or leave the cluster and re-elect a new cluster head, while the event is moving. As a physical event may split into two sub-events with the same nature, we propose also a cluster split mechanism that allows the user to monitor the event split and the new resulting events.

This chapter is organized as follows: section 5.1 presents a background and brief review of related work found in literature. Section 5.2 presents the suggested clustering protocol. Evaluation is provided in section 5.3, and a summary in section 5.4.

5.1 Background

As described in our literature review in chapter 2, many works have been proposed in the area of mobile event monitoring using different techniques [Brooks'03] [Li'02, Tseng'03]. However, these works fail to propose an energy efficient solution to the problem as they do no consider the collaboration aspect of wireless sensor networks. More recent works used clustering approach to establish coordination between sensor nodes [Chen'04, Fang'03]. The work proposed in [Chen'04] is among the first protocols to use clustering in target applications. In this work the authors propose an acoustic target tracking clustering protocol that groups sensor nodes detecting an acoustic signal with a certain threshold in a cluster. These sensor nodes report their data to a highly capable node that is considered as the cluster head. While the tracked object is localized with precision, this work does not consider the energy constraint as it assumes a heterogeneous wireless sensor networks containing a number of high capabilities sensor nodes. The protocol proposed in [Fang'03] uses another clustering technique as sensor nodes detecting the same event are grouped in an aggregate. To join the aggregate each node needs to apply a decision predicate in order to find out if its signal exceeds the specified threshold. In this protocol, the sensor node that has the highest signal is elected as an aggregate leader. However, the clustering approach used in these works is not flexible enough as it does not use an update mechanism for nodes in the cluster. Indeed, these protocols do not propose any solution to maintain the cluster and prefer instead to re-build a new cluster each time the monitored event changes position. In situation where event speed is high, such static clustering approach becomes very energy consuming.

5.2 An Energy Efficient Clustering Protocol for Mobile Event Monitoring

In this section we describe how we adapt our semantic clustering protocol to deal with mobile events and the different elements added to it. The key element in this work is the cluster membership update mechanism which helps to maintain the same cluster while nodes may join or leave or a new cluster head may be elected. In addition, as the monitored event may split; we propose a cluster split scheme in order to follow the two new generated objects. As sensor nodes can be equipped with a GPS receiver or the position can be determined by means of locations techniques [Hightower'01], we assume in the following that a grid of location aware, sensors is deployed in a study field where each location is reported by its X and Y coordinates.

First, we use our semantic clustering protocol presented in chapter 4 to form the cluster that group nodes within the event area. Once the cluster formed, nodes start sending their readings towards the cluster head. The data is aggregated at each parent node in the tree using a *Max aggregator*, in order to find the node with the highest reading. The node with the highest reading will be elected as cluster head, and all nodes within the cluster will update their links with their neighbours according to the new cluster head position. Cluster members continue to send their readings periodically to the cluster head, and each period the cluster head determines the nearest node to the event source. The nearest node to the event source will be elected as the new cluster head.

5.2.1 Concepts and Definitions

As discussed in our environment model, an event that occurs in the study field is detected by only a subset of sensor nodes. To determine this subset of sensor nodes we define two thresholds: a high threshold *T1* and a low threshold *T2*, as illustrated in figure 5-1.

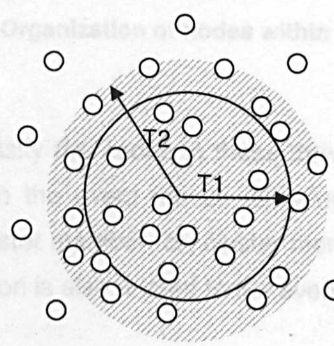


Figure 5-1: Event areas defined by two thresholds

Using the semantic clustering protocol described in chapter 4, it is possible to build a cluster grouping nodes detecting the tracked event with a signal higher than *T1*, and using the two thresholds *T1* and *T2* we can identify three types of sensor nodes: *cluster members nodes*, *cluster borders nodes*, and *idle nodes*, as illustrated in figure 5.2.

(i) Cluster member nodes: These are the nodes which detect the event with a signal exceeding T1 and thus are within the event area.

(ii) Cluster border nodes: These are the nodes which detect the event with a signal less than T1 but higher than T2.

(iii) Idle nodes: These are the nodes that detect the event with a signal less than T2 or do not detect the event.

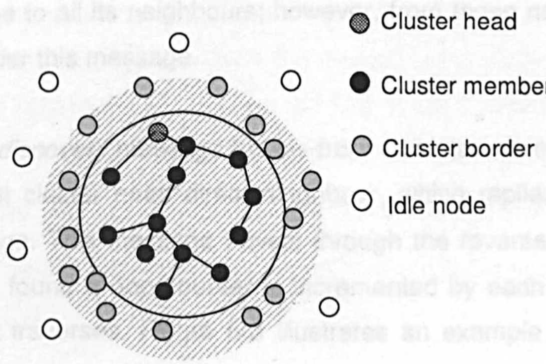


Figure 5-2: Organization of nodes within the event area

The main reason to classify the nodes in these three categories is to facilitate the information update when the event moves following nodes status transition: Idle node, cluster border, cluster member, or: cluster member, cluster border, idle node. The nodes status transition is also related to the event speed and moving direction.

5.2.2 Cluster Head Re-Election

An efficient way to determine if the event moves is to locate, each period of time, the nearest node to the event source. As an initial phase, each node upon joining the cluster sends a location report indicating its readings and its location. As mentioned earlier the node with the highest reading is usually the nearest node to the event source. Thus, by applying a *Max* aggregation operator at each parent node in the tree, the cluster head could determine the nearest node to the event source. Once the nearest node is determined, the cluster head broadcasts a *cluster-head-re-election* message to all the cluster members, this message contains the *id* of the elected cluster head.

Each cluster member upon receiving the *cluster-head-re-election* message checks the *id* field in this message, if the cluster member finds that it has the same *id* it becomes cluster head. If the cluster member is not the new elected cluster head it checks if it is one of its direct neighbours which are either its parent or its children in the tree. If the new cluster head is one of its direct neighbours, then it leaves its parent and chooses the new cluster head as its new parent. If the cluster member does not find the new cluster head in its list of neighbours, it sends a *cluster-head-path-discovery* message to all its neighbours; however, from those neighbours only cluster members consider this message.

The *cluster-head-path-discovery* message travels from a cluster member to another until it reaches the first cluster head direct neighbour, which replies with *cluster-head-path-reply* message. This message travels through the reverse path. In case where many paths are found a hop counter is incremented by each node that the *cluster-head-path-reply* traverses. Figure 5-3 illustrates an example of the cluster head re-election procedure.

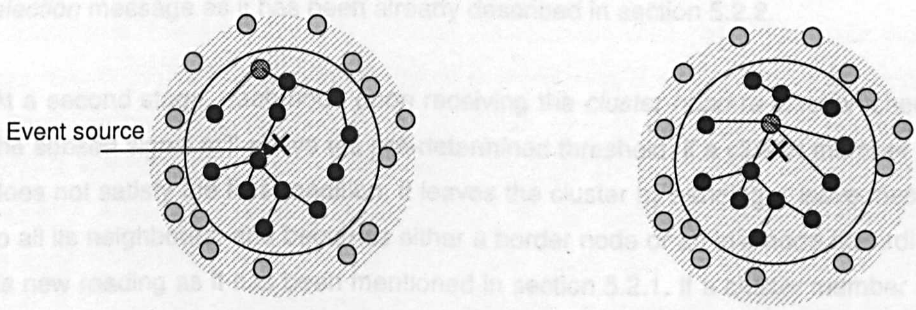


Figure 5-3: Cluster head re-election example

5.2.3 Cluster Membership Update Scheme

As mentioned earlier, the cluster membership update scheme represents a key element in our mobile event monitoring protocol. In this scheme, each node upon joining the cluster starts sending its sensed data to the cluster head in *data* packets, each *data update interval* (DUI). The value of this time interval can be decided by the application profile and the monitored event speed. A *data* packet contains the node's *id* and its reading. This will help the cluster head to determine if the event has changed position.

The data travelling from the sensor members to the cluster head is aggregated using a *Max* aggregator, allowing the cluster head to receive only the highest reading and its corresponding node *id*. Once the cluster head receives these *data* packets it compares the aggregate with its own reading. If the cluster head finds that there is node that has a reading n higher than its own reading n_{CH} and $n - n_{CH} > \Delta n_{th}$, where Δn_{th} is a threshold specific to the application predefined by the user, the cluster head detects that the event has moved and then initiates a cluster membership update.

At a first stage, the cluster head elects the node with the highest reading as the new cluster head and informs all the cluster members by broadcasting *cluster-head-re-election* message as it has been already described in section 5.2.2.

At a second stage, each node upon receiving the *cluster-head-re-election* checks if the sensed signal still above the pre-determined threshold. If a cluster member node does not satisfy the first condition, it leaves the cluster by sending a *leave* message to all its neighbours, and becomes either a border node or an idle node according to its new reading as it has been mentioned in section 5.2.1. If a cluster member node finds that it still satisfies this condition it starts looking for the shortest path towards the new cluster head and updates its parent-children links as it has been already described in section 5.2.2.

Cluster border nodes, however; do not have to wait for a *cluster-head-re-election* packet to join the cluster. If a cluster border node finds that its reading exceeds the threshold *T1* it becomes a cluster member and sends a join message to the first node from which it has received the *advertisement* packet. This node becomes its parent in the tree. After joining the cluster, the new cluster member broadcasts an *advertisement* packet to its neighbours, before it starts sending periodically its readings towards the new cluster head through its parent.

Figure 5-4 illustrates an example of the cluster membership update process.

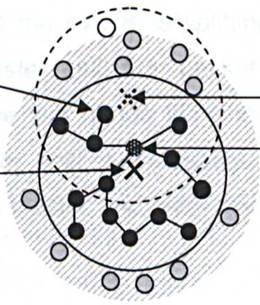


Figure 5-4: Cluster membership update example

5.2.4 Cluster Split Scheme

In the real life it is possible that a physical event generates many other sub-phenomena. For instance, it is possible that a monitored gas cloud splits into two gas clouds. Since the user is interested in monitoring the air quality, it is necessary to split the cluster formed around the event as well. As the event split into two sub-events with the same nature, two event sources are generated. According to the mobility scheme presented earlier, each cluster member sends periodically its reading towards the cluster head. The cluster head, upon receiving those readings should choose the node with the highest reading as the new cluster head. However, in the case where two events are present, it is necessary to determine the nearest nodes to the two event sources.

With our cluster membership update scheme, we could only determine the node with the highest reading among the cluster members, and neglecting other readings. In the case where the two nearest nodes to the new event sources send their readings to the cluster head, the cluster head will peak up only the node with highest reading. Thus, only one event will be considered and the cluster update will converge towards this event only.

One way to solve this problem is to introduce the position of each cluster member in the periodically reading message, which allows the cluster head to calculate the distance between two nodes having the highest sensed signal. We introduce split distance threshold D_{split} as a threshold in order to detect the event split. If any parent node or the cluster head receives two high readings coming from two nodes and estimate from their positions that the distance separating them exceeds the threshold D_{split} it decides that the events is splitting. A cluster member that detects the event split sends a *cluster_split_adv* packet towards the cluster head. The *cluster_split_adv* contains the two nodes ids and their respective readings. If the cluster head receives a *cluster_split_adv* message or detects a cluster split by itself, then it will decide to split the cluster and elect the two new nodes as cluster heads for the new resulting clusters.

The cluster split operation is initiated by the original cluster head and starts by sending a *cluster-split-advertisement* packet to all cluster members. The *cluster-split-advertisement* message contains: the original cluster head *id*, the *ids* and positions of both new cluster heads. Each node upon receiving this message performs almost the same cluster membership update operation already described in section 5.3.2. However, unlike the membership update scheme, each node will not estimate its distance from one cluster head but from the two elected cluster heads, and chooses the nearest one to it as its cluster head. Upon the cluster split is over, all cluster members will send their new readings towards their new cluster head through the new established tree within each cluster. Figure 5-5 illustrates an example of cluster split.

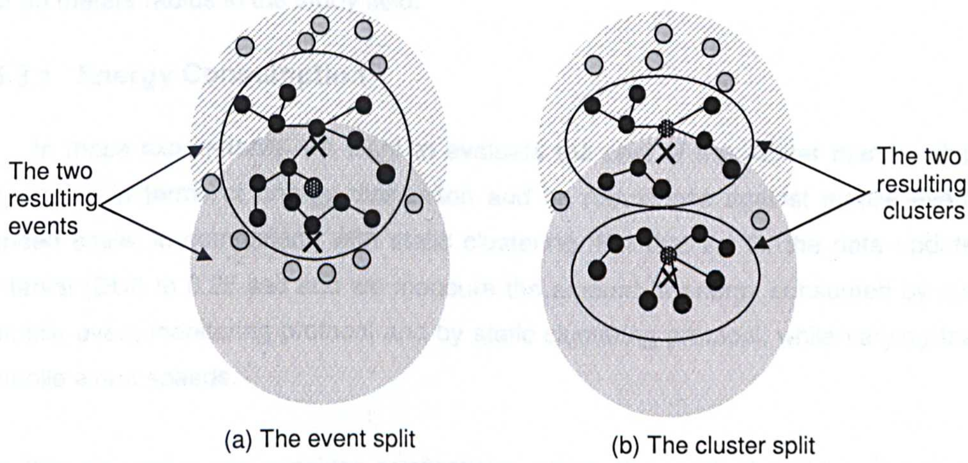


Figure 5-5: Cluster split example

5.3 Evaluation

In this section we evaluate our mobile event monitoring protocol through simulation. For that we use the same environmental and radio energy models presented in chapter 2 with the same simulation environment and parameters described in chapter 3. We set also the data packet size to 525 bytes. In these simulations, our mobile event monitoring routing protocol is compared with the static clustering approach used in [Chen'04]. This comparison is in terms of energy dissipation and robustness against mobile event speed scale. The main goals we want to achieve through these simulations are:

(i) To assess the energy efficiency of our clustering protocol and study the influence of the event speed on its performance.

(ii) To study the impact of the data update interval (DUI) on the performance of the protocol and determine the adequate time interval value to achieve the best performance.

(iii) To assess the cluster split efficiency in the case of an event split and its performance.

We simulate a network of 900 sensor nodes uniformly distributed, where the distance separating each two nodes is 10 meters. We simulate also a mobile event of 30 meters radius in the study field.

5.3.1 Energy Consumption

In these experiments, we want to evaluate the cost of the cluster membership operation in terms of energy dissipation and its robustness against mobile event speed scale, in comparison with static clustering. For that we fix the data update interval (DUI) to 0.25 sec and we measure the amount of energy consumed by our mobile event monitoring protocol and by static clustering protocol, while varying the mobile event speeds.

In this simulation we consider applications where the tracked mobile source is carried in a car. For that we vary the speed between 10m/sec (22.5mph) and 30m/sec (67.5 mph).

Figures 5-6, 5-7, and 5-8 show the amount of energy consumed by the network using both approaches over time for the respective event speeds: 10 meter/sec, 20 meter/sec and 30 meter/sec.

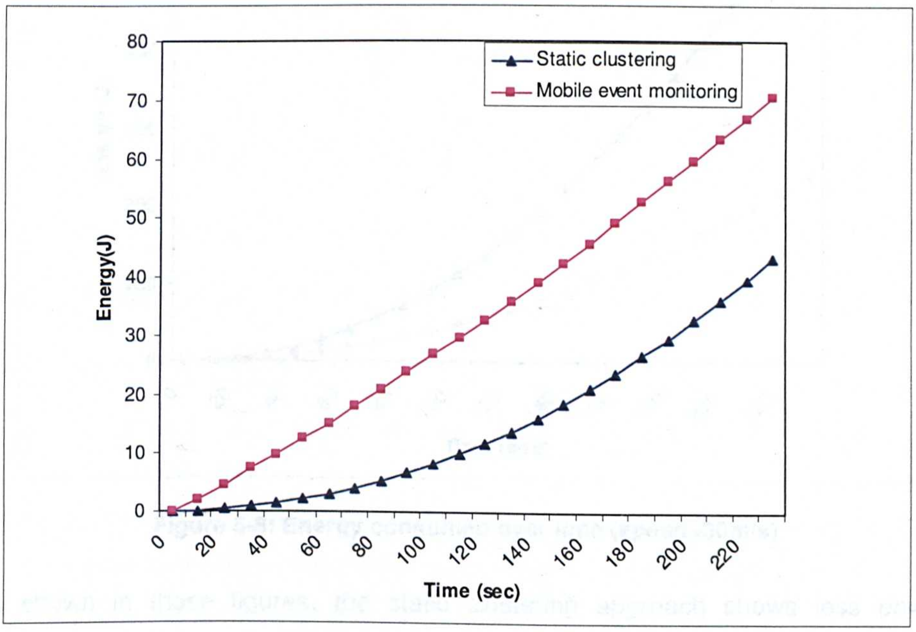


Figure 5-6: Energy consumed over time (speed=10m/s)

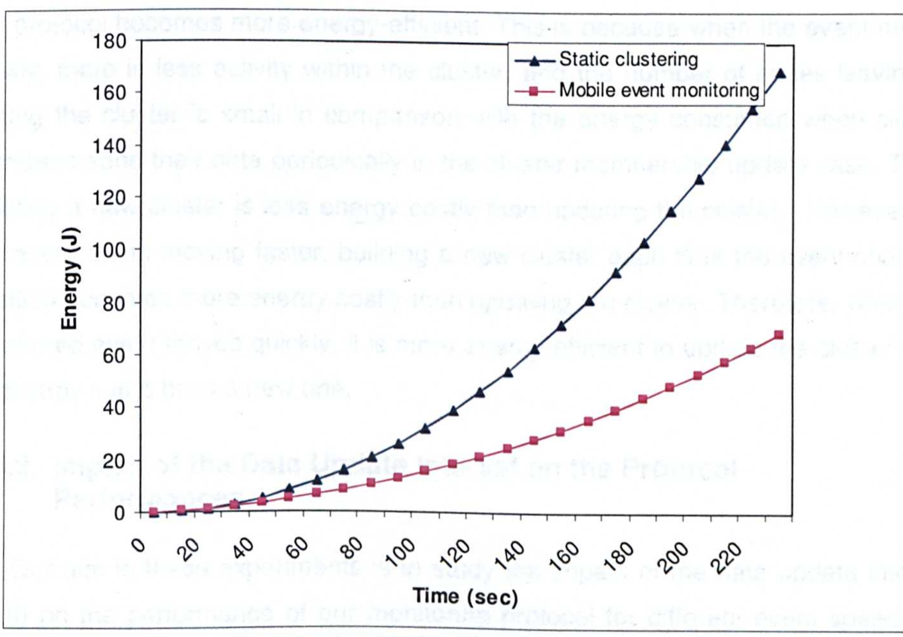


Figure 5-7: Energy consumed over time (speed=20m/s)

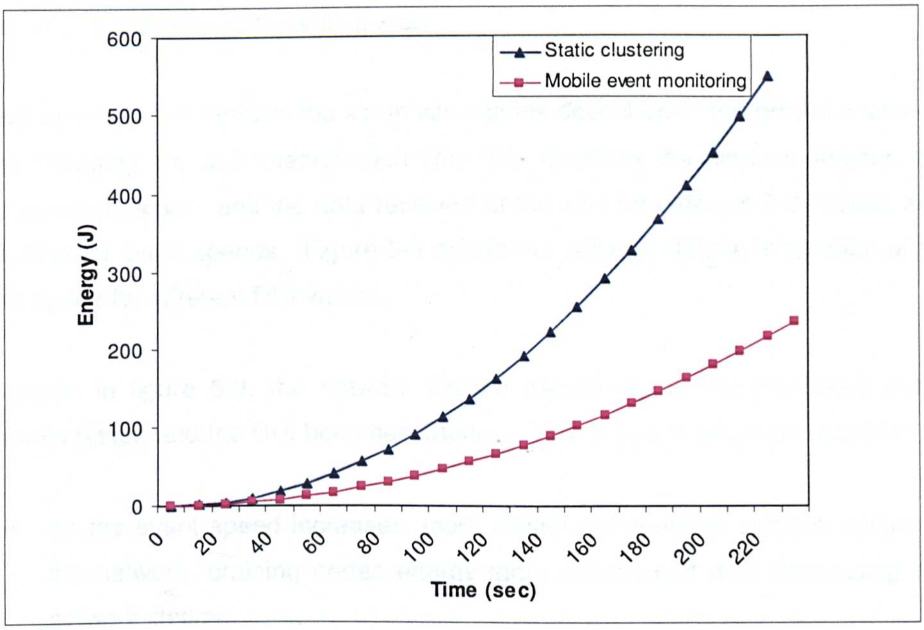


Figure 5-8: Energy consumed over time (speed=30m/s)

As shown in these figures, the static clustering approach shows less energy consumption than our mobile event monitoring protocol, when the event speed=10 meter/sec. However, when the event speed starts increasing (speed>=20meter/sec), our protocol becomes more energy-efficient. This is because when the event moves slowly, there is less activity within the cluster, and the number of nodes leaving or joining the cluster is small in comparison with the energy consumed when cluster members send their data periodically in the cluster membership update case. Thus, building a new cluster is less energy costly than updating the cluster. However, as the event starts moving faster, building a new cluster each time the event changes position becomes more energy costly than updating the cluster. Therefore, when the monitored event moves quickly, it is more energy efficient to update the cluster than to destroy it and build a new one.

5.3.2 Impact of the Data Update Interval on the Protocol Performances

Our aim in these experiments is to study the impact of the data update interval (DUI) on the performance of our monitoring protocol for different event speeds, in terms of energy consumption and data accuracy. We want to evaluate also the efficiency of our cluster membership update scheme to maintain the cluster under variable DUI intervals and event speeds.

To achieve that, we perform the same simulations described in the previous section while changing the DUI interval each time. We measure the network lifetime, the energy consumption, and the data received at the sink for different DUI values and with different event speeds. Figure 5-9 shows the network lifetime in function of he event speed for different DUI values.

As shown in figure 5-9, the network lifetime decreases as the monitored event becomes faster, and the DUI becomes shorter. This is due to two main reasons:

- As the event speed increases, more cluster membership updates occurs in the network, draining nodes energy more quickly and thus decreasing the network lifetime.
- As the DUI becomes shorter, the sensor nodes send more data packets towards the cluster head which increases the energy consumption and, thus; reduce the network lifetime.

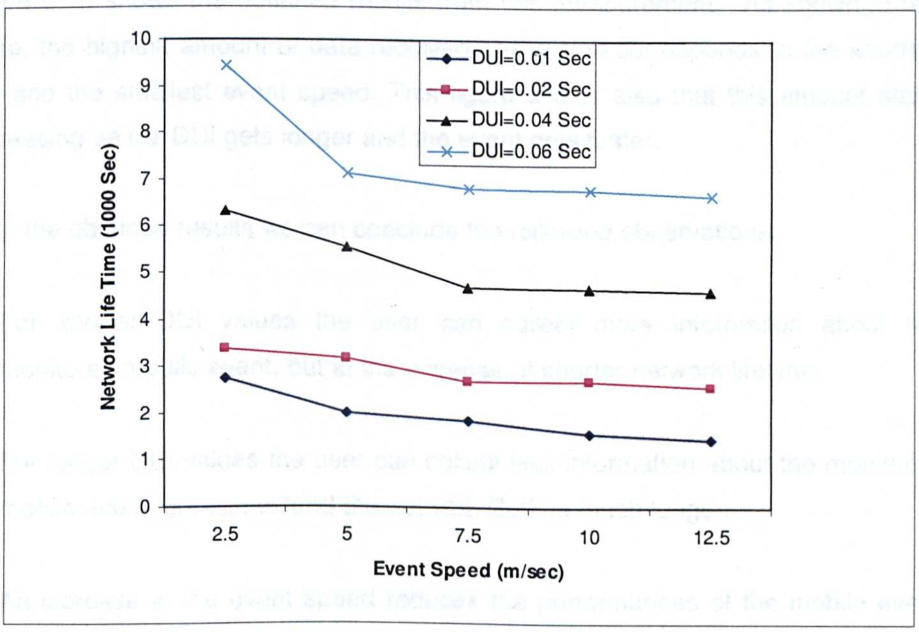


Figure 5-9: Network lifetime over the event speed

We measured the amount of data received at the sink during the network lifetime for the different the events speed and different DUI values.

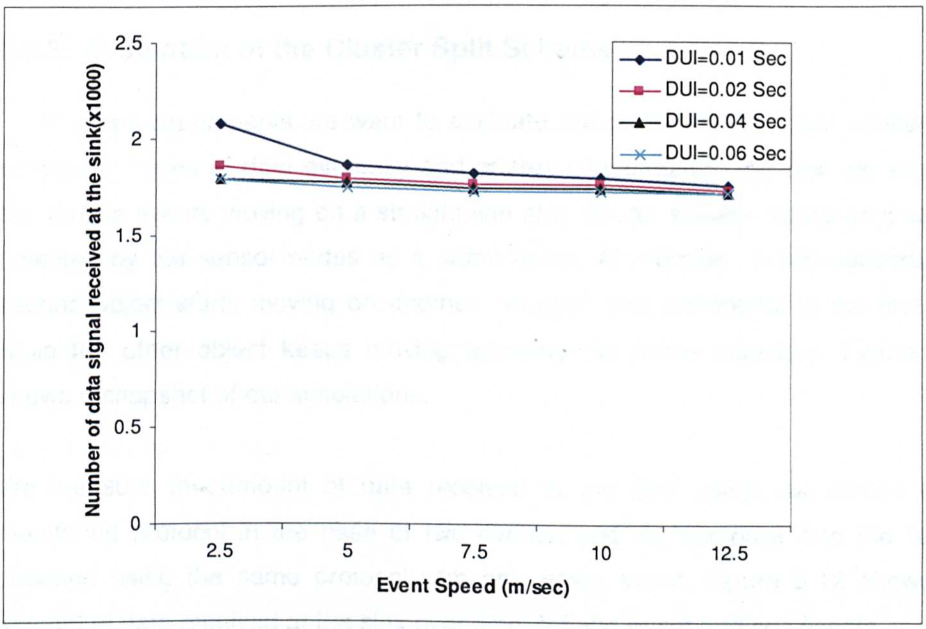


Figure 5-10: Amount of data received at the sink

Figure 5-10 shows the obtained results from this measurement. As shown in this figure, the highest amount of data received at the sink corresponds to the shortest DUI and the smallest event speed. This figure shows also that this amount starts decreasing as the DUI gets longer and the event gets faster.

From the obtained results we can conclude the following observations:

- For shorter DUI values the user can collect more information about the monitored mobile event, but at the expense of shorter network lifetime.
- For longer DUI values the user can collect less information about the monitored mobile event, but can extend the network lifetime much longer.
- An increase in the event speed reduces the performances of the mobile event monitoring protocol in terms of data gathering, and network lifetime.

- By decreasing the DUI interval it is possible to improve the performances of the mobile event monitoring protocol in terms of data gathering especially when the mobile event is moving very fast.

5.3.3 Evaluation of the Cluster Split Scheme

In these experiments we want to evaluate the performance of our cluster split scheme in terms of data accuracy and energy consumption. For that we simulate two mobile events moving on a straight line at a regular speed= 10m/s so it can be detected by the sensor nodes as a same event. At moment t=100 seconds, the second object starts moving on another straight line orthogonal to the first one, while the other object keeps moving following the same trajectory. Figure 5-11 shows a snapshot of our simulations.

We measure the amount of data received at the sink using our mobile event monitoring protocol in the case of two events, and we compare it to the results obtained using the same protocol with only when event. Figure 5-12 shows the amount of data received at the sink over time, for one event and two events.

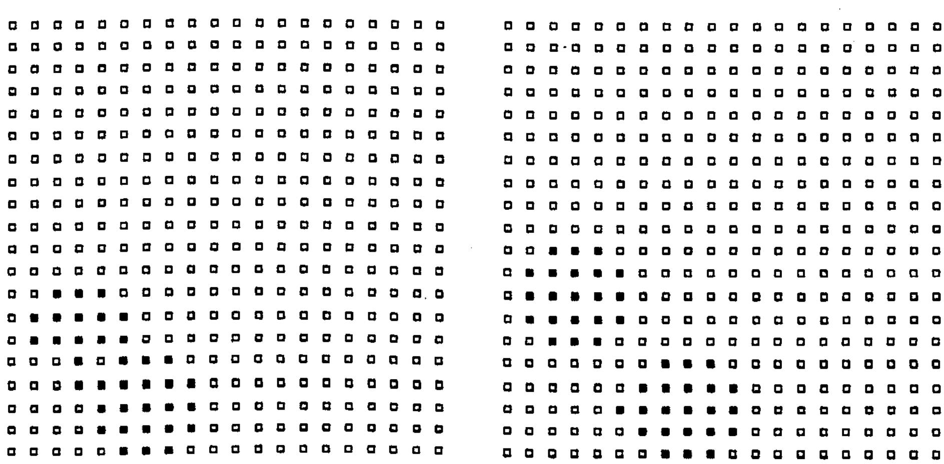


Figure 5-11: Example of cluster split through simulations

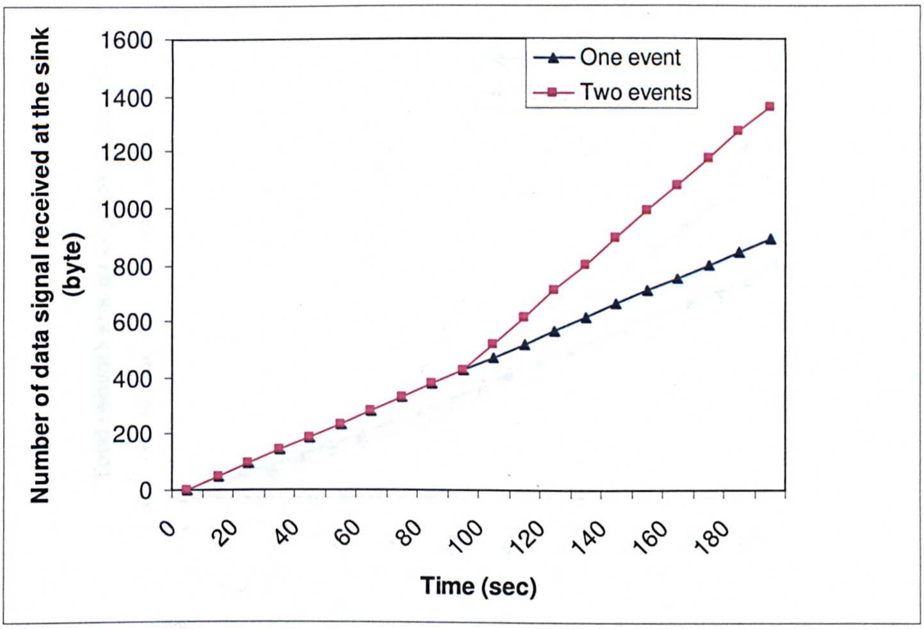


Figure 5-12: Amount of data received at the sink over time

As shown in figure 5-12, the amount of data received at the sink is the same for both scenarios until the moment t=100 sec. At this moment the amount of data in the scenario of two events starts increasing more significantly than in the scenario of one event, which indicates that sensor nodes have detected the second event and started sending information about the second event to the user.

To evaluate the cost of the cluster split operation in terms of energy consumption we measured the energy dissipated in the network for both scenarios: one event and two events. Figure 5-13 shows the amount of energy consumed by the network over time for both cases one event and two events.

As shown in figure 5-13, the energy consumed in the two scenarios is almost the same until the moment t=100sec. Starting from this moment the amount of energy consumption in the two events scenario starts increasing considerably in comparison with the one event scenario. This is because, the event split procedure involves more nodes in the monitoring process which implies that more data packets are exchanged.

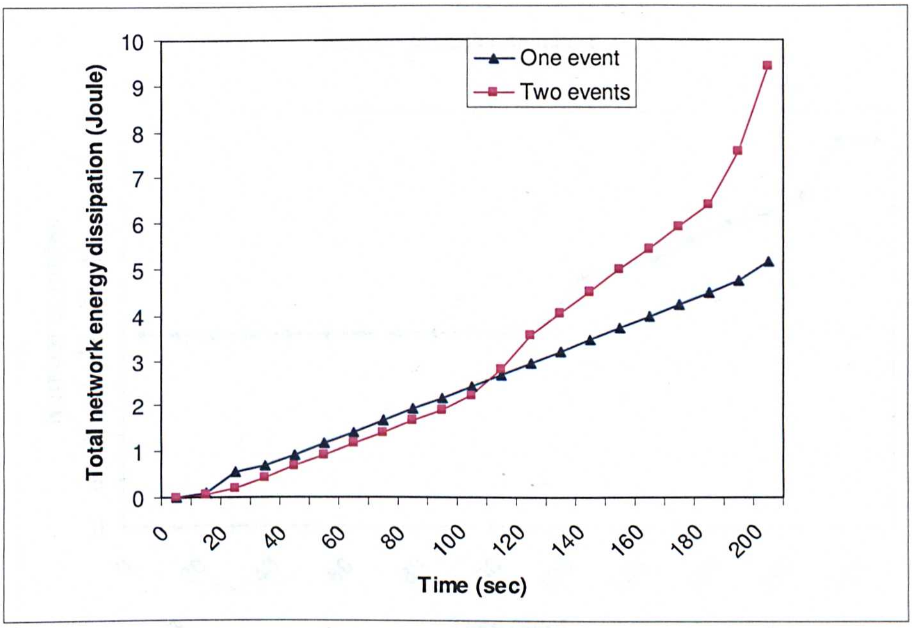


Figure 5-13: Energy consumed in the cluster split process over time

Figure 5-13 shows also that unlike the amount of data received at the sink, the increase in the energy consumption in the case of cluster split is not uniform all the time. This is because:

- The sink receives only the data sent by the cluster heads and as the cluster split generates two cluster head the amount of data received by the sink increases uniformly.

- The increase of the number of nodes involved in the monitoring is not uniform as it is shown in figure 5-14.

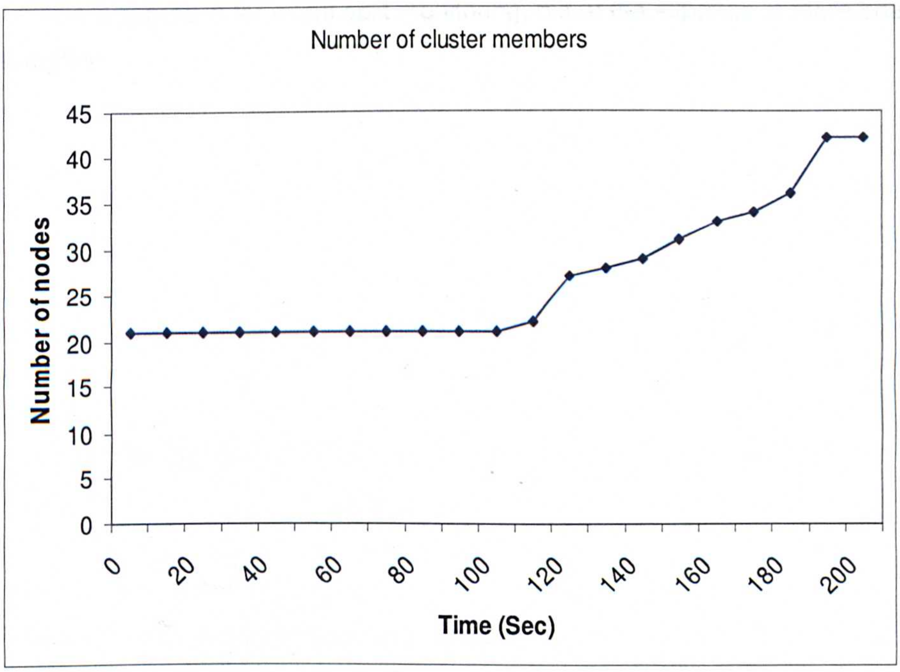


Figure 5-14: Number of cluster members in the cluster split process over time

5.4 Summary

In this chapter, we proposed and evaluated a fully decentralized, dynamic clustering protocol for mobile event monitoring. Using the semantic clustering protocol proposed in chapter 4, we group nodes within the observed event area in the same cluster. We designed a cluster membership update scheme that maintains the cluster while the event is moving. This scheme uses the data packets sent periodically by the cluster members to determine if the event has moved, and launch a cluster head re-election phase followed by an update of the cluster members' status. We addressed the event split monitoring issue by proposing a cluster scheme mechanism.

We showed through simulations that our protocol achieves better energy saving than existing approaches, especially when the monitored event is moving very fast. We investigated the impact of the data update interval on the performance of the cluster membership update scheme. We showed also that the cluster split scheme is an efficient approach for event split monitoring, but at the expense of more energy consumption.

6 A Node Recovery Scheme for Data Dissemination

Wireless sensor networks consist of densely deployed sensor nodes capable of sensing particular physical events in their vicinity and communicating between themselves using wireless transceivers. These tiny sensor nodes are usually deployed in various environments to collectively gather data required by the user and deliver them to the sink.

Such sensing delivery operation may include several hops among the resource-limited sensor nodes. If a sensor node on the data dissemination path runs out of energy, the whole delivery operation will be compromised. Therefore, the challenge is to design a solution that makes the data dissemination more reliable and extends the routing path lifetime as much as possible.

As described in chapter 2, several algorithms and protocols have been developed in the last few years, with the goal of achieving more efficient and reliable data dissemination in wireless sensor networks. Most of these routing protocols use a single path approach to transmit the data to the user. In such an approach, the optimal path is generally selected according to a predefined metric such as the gradient of information, the distance to the destination or the node residual energy level [Huang'05, Xu'01].

However, although the single path approach achieves shortest delay and involves minimum number of nodes, it concentrates the traffic on the same path. In case of continuous data transmission such approach may result in energy exhausted nodes and the loss of the network connectivity.

On the other hand, some other routing protocols that use multipath dissemination choose the network reliability as their design priority. In this approach the data delivery relies mostly on the optimal path. The alternative paths are used only when some nodes on the primary path fail. In [Nasipuri'99] and [Marina'01] , a multipath extension of Dynamic Source Routing (DSR) and Ad hoc On-demand Source Routing (AODV) were proposed to improve the energy efficiency. In directed diffusion [Intanagonwiwat'00] the flooding of interest by the sinks allows the gradients to be set within the network. In [Ganesan'02] a multipath routing approach is proposed for directed diffusion to improve resilience to nodes failure, by exploring the possibility of finding alternate paths connecting the source and sinks when node failures occur. In [Barrett'03] a probabilistic routing protocol is proposed which uses a retransmission probability function to reduce the number of copies of same data. This probability function use the hop distance to the destination and the number of steps that the data packets have travelled as parameters. In [Chang'00] the multipath routing is formulated as linear programming problem with an objective to maximize the time until the first sensor node runs out of energy. The sources are assumed to be transmitting data at a constant rate.

Although the multipath approach achieves reliable data dissemination, the use of several paths and the frequent changing of routing paths result in higher energy consumption especially if the source is far away from the sink.

In this chapter, we present a node recovery scheme for data dissemination in wireless sensor networks. By exploiting the network density and the broadcasting nature of the wireless medium, we propose to replace the energy drained nodes by other neighbouring nodes that can relay the data from the source to the destination, without changing the routing path.

This chapter is organized as follows: Section 6.1 introduces our new node recovery scheme and describes its different phases. Section 6.2 studies the impact of the wireless sensor networks parameters such as the network density and the sensor nodes radio range on the recovery scheme. In section 6.3 we evaluate our protocol by simulations and in section 6.4 we present a summary of our work.

6.1 A Node Recovery Scheme for Data Dissemination

As sensor nodes are usually densely deployed and due to the broadcasting nature of wireless channel, it is possible that nodes overhear another node's transmission if they are within its transmission scope. Although this redundant reception might result in further energy consumption; it can be useful to recover nodes failure in the routing process, as it is illustrated in figure 6-1.

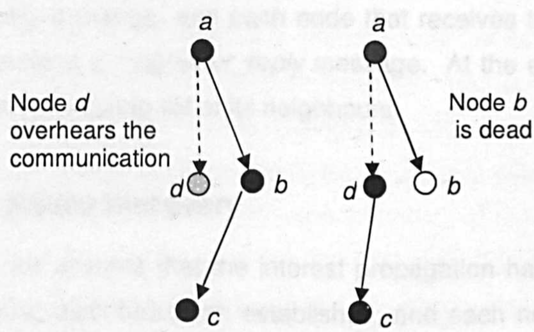


Figure 6-1: An example of node recovery

However, such recovery needs to be organized in order to allow each node on the data dissemination path to discover its potential recovery node if it exists.

Our recovery scheme can work with any gradient routing protocol like directed diffusion or our semantic clustering protocol described in chapter4. Using any of these routing protocols we assume that a source node *S* is sending data to the sink following an already defined path.

We introduce the two entities involved in our recovery scheme: the *upstream neighbour entry*, and the *downstream neighbour entry*. The upstream neighbour entry is the memory space used by each node to save the id of the neighbour from which it receives data packet to send it towards the sink. The downstream neighbour entry is the memory space used by each node to save the id of the neighbour from which it receives the interest and the corresponding number of hops to the sink. In other words the upstream neighbour represents the previous node in the routing path and the downstream neighbour represents the next node in the routing path. Our recovery scheme consists of three phases:

- Neighbour discovery phase.
- Recovery nodes discovery phase.
- Dead node recovery phase.

6.1.1 Neighbours Discovery

This operation starts at the deployment time and aims to inform each sensor node about its neighbours. Upon deployed, each sensor node broadcasts a *neighbours_discovery* message, and each node that receives this message replies to the sender by sending a *neighbour_reply* message. At the end of this operation each node will have a complete list of its neighbours.

6.1.2 Recovery Nodes Discovery

For this phase we assume that the interest propagation has been successfully finished and a routing path has been established, and each node in the path has saved the previous node id and the next node id in the upstream neighbour and downstream neighbour entries.

When the routing path is defined each node on the path starts looking for a recovery node by broadcasting *recovery_node_discovery* to its neighbours containing: its id, the *upstream neighbour* id, and the *downstream neighbour* id. If a node *m* receives a *recovery_node_discovery* message from a node *n* on the routing path, it starts looking for the *upstream neighbour* and *downstream neighbour* in its neighbours list. If the two nodes' ids are found, which means that it has both the nodes as neighbours, the node *m* declares itself as a potential recovery node for node *n*. The node *m* sets then a timer for a random but short period of time T_{wait}, after which it sends a *recovery_node_reply* message to the node *n*. The node *m* is considered as the recovery node for the node *n*. If within the period T_{wait} , the node *m* hears another *recovery_node_reply* message towards the node *n* it cancels the transmission. This mechanism helps to reduce the number of the *recovery_node_reply* transmissions. This operation will be repeated for all nodes in the routing path from the source to the sink, so that each node on the path will have a known recovery node. Note that all recovery nodes once known turn their radio systems to the overhearing mode.

6.1.3 Dead Node Recovery

Suppose that the node *n* is a sensor node on the routing path and *m* is its recovery node. When the node *n* receives a data packet to forward towards the sink, the node *m* overhears the transmission and set a timer T_{transmit} and waits for the node *n* to transmit the data packet to its downstream neighbour. If the timer T_{transmit} expires and the node *m* still did not hear the transmission from *n* to its downstream neighbour, it considers the node *n* as dead, and forwards the data packet instead. The node *m* then informs both the upstream neighbour and downstream neighbour of node *n* that it is the new node on the routing path. Consequently all three nodes start another recovery node discovery sequence as already described in the section 6.1.2.

6.2 Network Density and Transmissions Overhearing

The success of our proposed scheme depends upon finding a recovery node for each node in the routing path. In this section we will discuss the probability of finding a recovery node, and the factors that affect this probability.

Since sensor nodes are equipped with wireless radio transceivers, their scope of transmission is limited. As the propagated signal strength decays exponentially with respect to distance [Shankar'02], the radio coverage area can be simply modelled as a disk where the transceiver is at the centre. The diameter of this disk is considered as the radio range of the transceiver, as it is illustrated in figure 6-2.

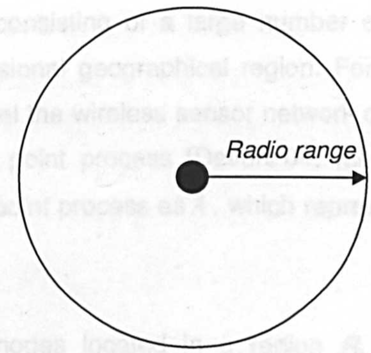


Figure 6-2: Radio coverage model

Figure 6-3 illustrates an example of a one hop transmission between node *a* and node *c* through node *b*. To make this communication possible it is necessary to have node *b* within the radio coverage area of both nodes *a* and *c*. Consequently, increasing the number of nodes within this area increases the chances of recovery and maintaining the network connectivity much longer. As sensor nodes are usually randomly and densely deployed it is important to study what factors can help to increase the chances of nodes recovery and maintain network connectivity.

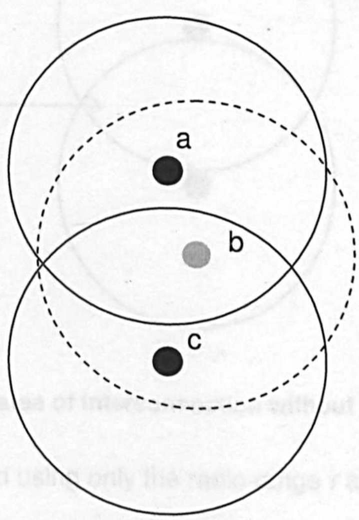


Figure 6-3: Wireless communication model

We consider a network consisting of a large number of sensor nodes deployed randomly in a two-dimensional geographical region. For convenience and for the sake of simplicity we model the wireless sensor network deployment by a stationary two-dimensional Poisson point process [Devore'04, Mhatre'05]. We denote the density of the underlying point process as λ, which represents the number of nodes per m^2.

The number of sensor nodes located in a region *R*, *N(R)*, follows a Poisson distribution of parameter $\lambda\|R\|$, where $\|R\|$ represents the area of the region, as following:

$$P(N(R)=k)=\frac{e^{-\lambda\|R\|}(\lambda\|R\|)^k}{k!} \qquad (6\text{-}1)$$

Figure 6-4 shows the maximum area of interconnection of two nodes radio coverage areas without possibility to communicate with each other, denoted R_{Max}.

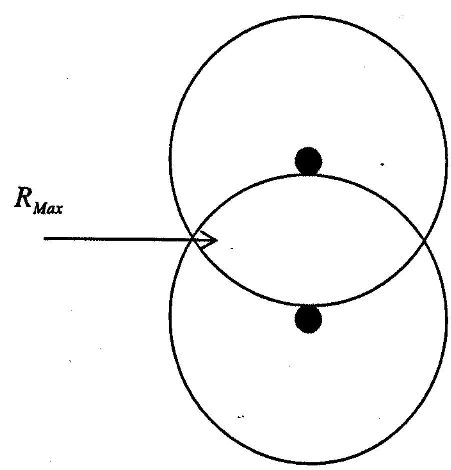


Figure 6-4: Maximum area of interconnection without direct communication

This area can be calculated using only the radio range *r* as following:

$$R_{Max}=Ct(r)=\frac{r^2(4\pi-3\sqrt{3})}{6} \qquad (6\text{-}2)$$

Details about the calculation of this equation are presented in the appendix A.

Consequently, knowing the area R_{Max} and by using the equation (6-2), it is possible to calculate the probability to have at least one recovery node for each node on the transmission path, by calculating the probability of having at least two nodes within the area R_{Max} as following:

$$P(N(R_{Max}) \geq 2) = 1 - P(N(R_{Max}) \leq 2) \qquad (6\text{-}3)$$

Where:

$$P(N(R_{Max}) \leq k) = \sum_{i=0}^{k} \frac{e^{-\lambda \|R_{Max}\|} (\lambda \|R_{Max}\|)^i}{i!} \qquad (6\text{-}4)$$

Figure 6-5 shows the probability of having at least two nodes within the area R_{Max}, for different network densities and different radio ranges.

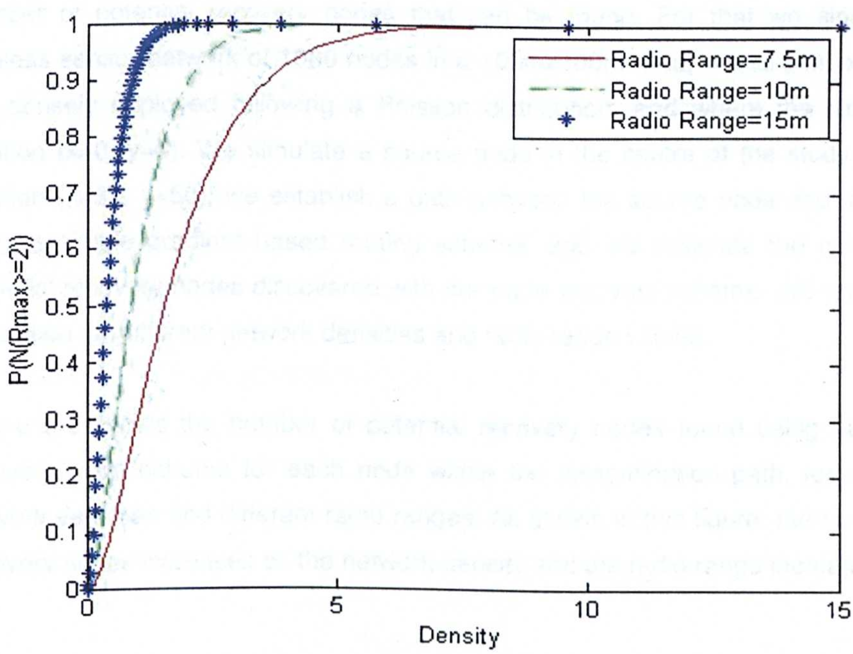


Figure 6-5: Probability of finding at least two nodes

As shown in figure 6-5, the probability of finding at least two nodes within the area R_{Max} increases as the network density and the radio range increase. We can see also in this figure that the probability of finding two nodes in the same area approaches the value 1 for a radio range equal to 15 meters and with a network density equal to 5. Since such radio range and network density values are generally satisfied in major wireless sensor networks, finding a recovery node for each node participating in the data dissemination is feasible.

6.3 Evaluation

We evaluate our node recovery scheme through simulation using the same simulator and with the same parameters presented in chapters 3. In these simulations we compare our node recovery scheme with single path data dissemination approach and multipath approach. The comparison with these two approaches is in terms of energy consumptions and network connectivity.

We firstly assess the analytical results obtained in the previous section about the number of potential recovery nodes that can be found. For that we simulate a wireless sensor network of 1000 nodes in a 100mx100m area, where sensor nodes are densely deployed following a Poisson distribution, and where the sink is at position (x=0, y=0). We simulate a source node in the centre of the study field at location (x=50, y=50), we establish a path between the source node and the sink, using a simple gradient based routing scheme, and we calculate the number of potential recovery nodes discovered with our node recovery scheme. We repeat the simulation for different network densities and radio range values.

Figure 6-6 shows the number of potential recovery nodes found using our node recovery node scheme for each node within the dissemination path, for different network densities and different radio ranges. As shown in this figure, the number of recovery nodes increases as the network density and the radio range increase.

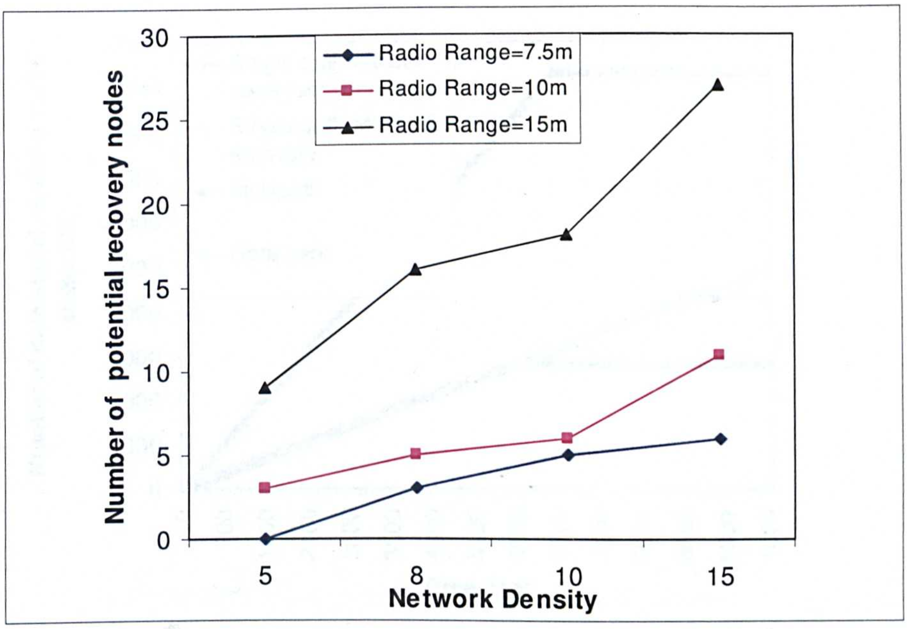


Figure 6-6: Number of discovered recovery nodes

At a second stage, we fix the network density $\lambda = 10$ (number of nodes per m^2) and the radio range to 7.5 meters and we measure the amount of data received at the sink and the number of nodes alive over time, using: single path approach without node recovery, single path approach with our node recovery scheme, and multipath approach.

Figure 6-7 shows the amount of data sent by the source and the amount of data received at the sink over time, with the three data dissemination approaches.

As shown in figure 6-7, the multipath approach generally delivers more data to the sink than the other approaches. However, if we compare the data amount delivered by this approach with the data amount generated by the source, we can see that the amount of data delivered by the multipath approach exceeds the originally amount generated by the source. This is because the multipath approach sends the data to the sink through several paths to ensure reliability, and thus the sink receives generally duplicated packets. Unlike the multipath approach, the single path approach associated with our node recovery scheme deliver the exact amount of data sent by the source, and this continues until the network dies.

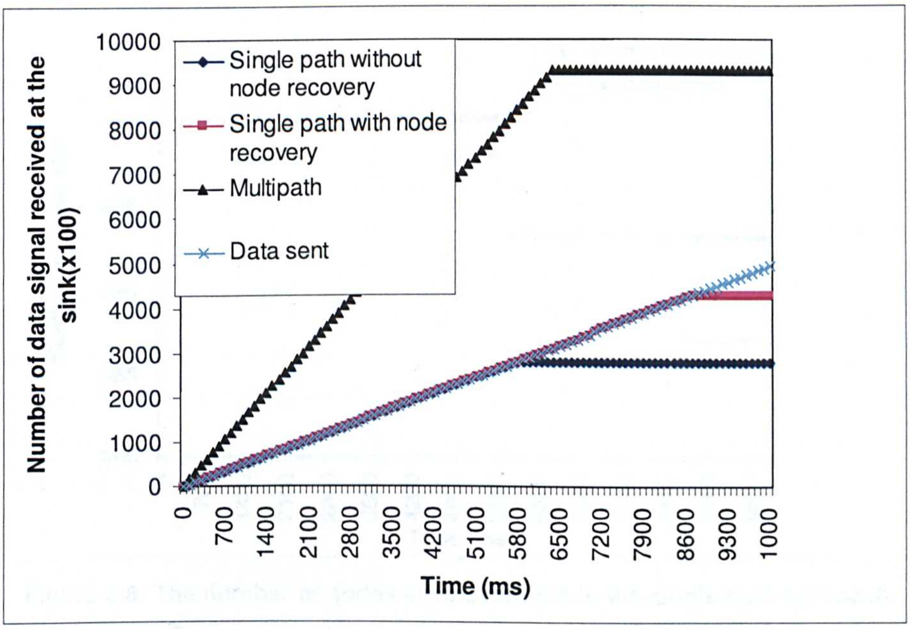


Figure 6-7: Amount of data sent and received over time

Form figure 6-7 we can see also that the single path approach without our node recovery scheme stops delivering data to the sink at the moment t=5800 ms, and the multipath approach stops delivering data to the sink at the moment t=6400 ms, while the single path approach associated with our node recovery scheme stops delivering data to the sink at the moment t=8700 ms. These results prove the efficiency of our node recovery scheme.

Figure 6-8 shows the number of nodes alive over time, using the single path approach with and without node recovery scheme. From figure 6-8 we can see that more nodes are used in the communication with the node recovery scheme than without it. This is because the node recovery scheme uses additional nodes to recover the energy drained sensor nodes and maintains the data delivery process. The additional dead nodes in the single path routing with recovery, shown in the figure 6-8 at the moment t=8700 ms, represent the recovery nodes used to extend the communication time.

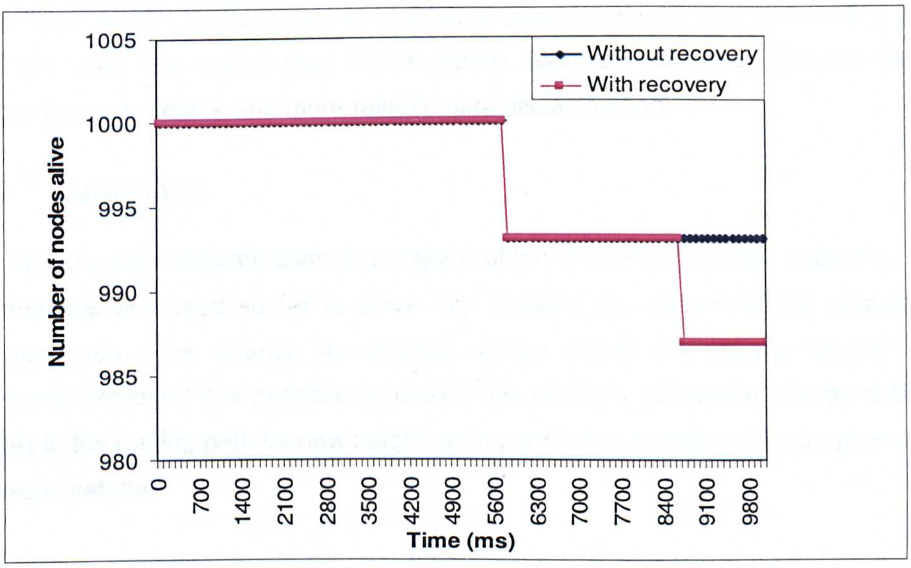


Figure 6-8: The number of nodes alive over time in the single path approach

We perform the same comparison between single path routing with node recovery and multipath routing as shown in figure 6-9.

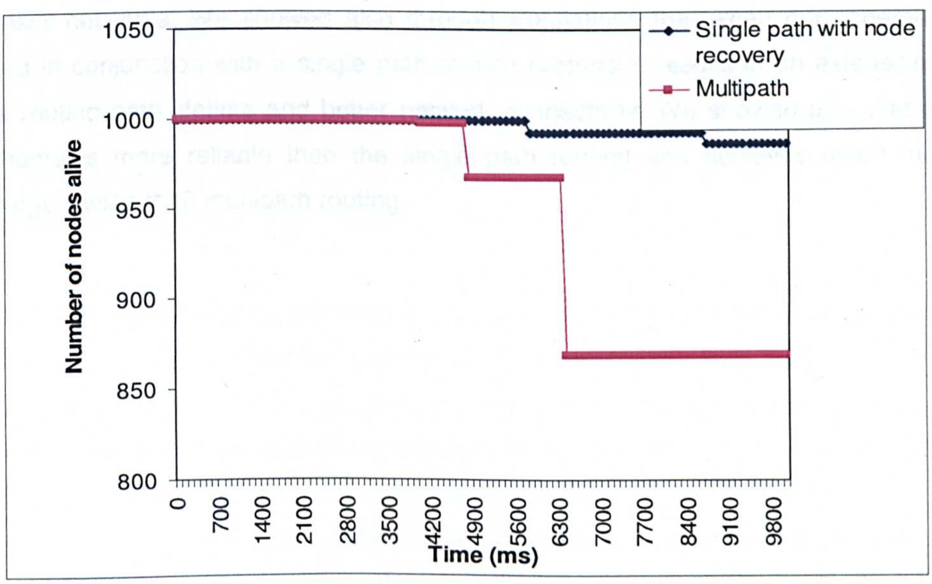


Figure 6-9: Multipath approach vs. recovery scheme

This figure shows that our recovery scheme associated with a single routing path solution uses less nodes than the multipath approach and thus provides better longer network lifetime and more reliable data dissemination.

6.4 Summary

Reliable data dissemination is a major problem in wireless sensor networks. The approaches proposed so far to solve this problem are either not too reliable or consume too much energy. As wireless sensor nodes are usually densely and randomly deployed it is possible to exploit this property to recover energy drained nodes in the routing path by new neighbouring and fresh sensor nodes to extend the network lifetime.

In this chapter we presented a new node recovery scheme that exploits the wireless sensor network density and the broadcasting nature of the wireless medium to recover energy exhausted nodes that are involved in the communication with the sink. We have shown through mathematical analysis and simulations that the conditions related to network density and the radio range that allow to find at least one recovery node for each node in the network, are mostly satisfied in wireless sensor networks. We showed also through simulations that when our scheme is used in conjunction with a single path routing protocol it results in an extension of the routing path lifetime and better network connectivity. We showed also that our scheme is more reliable than the single path routing and achieves much more energy saving than multipath routing.

7 A Coordination Framework for Single Actor Model

The ability to detect and monitor various physical phenomena is important for many applications. However, responding to these phenomena by performing the adequate actions in timely manner, is as important as detecting them. Sensor networks technologies have developed very quickly in the last few years. This kind of networks shows a big potential in the future security and monitoring applications. Although these networks were designed initially to detect and monitor physical events, they could be used actively by deploying active nodes called *actors*. Actors are nodes that could perform actions in the study filed according to information collected by sensor nodes. For instance, in fire detection application actors could be mobile engines equipped with necessary material to extinguish the fire.

Wireless sensor and actor networks design is aiming to perform the adequate action correspondent to the detected event with higher precision. Upon a detection of an event a sensor node must signal this event to an actor to deal with it. Thus, in addition to sensor to sensor communication, sensor to actor communication is needed. However, since sensor nodes are densely deployed, there is a high possibility that many nodes detect the same event and try to inform an actor independently from each other which could lead to an overlapping between many actors. The challenge is to design a communication scheme that offers coordination mechanisms between sensors and actors [Akyilidz'04].

Single-actor model is an important model in wireless sensor and actor networks. In this model, sensors readings must be sent to only one actor node. Even if one actor is not sufficient for the required action, that actor can publish an announcement message to other actors. This implies a low latency between sensing and acting, but without a need for actor to actor coordination.

In this chapter we address this problem by proposing a coordination framework for single actor model in wireless sensor and actor networks. The crucial challenge in this model is to find a way to inform each sensor node about its nearest actor while not consuming too much energy. Such information is really important, as the choice of the actor and the routing path depends on it. In this framework, nodes initially are organized in Voronoi diagram [Aurenhammer'00], where each actor builds a Voronoi region containing its nearest sensor nodes. Once an event is detected, sensor nodes within the event area are grouped using a semantic clustering protocol and the nearest node to the event source is elected as cluster head in order to inform the nearest actor.

This chapter is organized as follows: Section 7.1 reviews the major communications techniques found in the literature. Section 7.2 gives an overview on our coordination framework and describes its different phases. In section 7.3 we evaluate our solution by simulations, and in section 7.4 we summarize our work.

7.1 Background

As described in chapter 2 many routing protocols have been proposed in the area of wireless sensor networks. These protocols are primarily designed to achieve resources saving and extend the network lifetime. Such criterions are not enough to make these protocols efficient in wireless sensor and actor networks, and do not solve the problem of coordination as well.

The problem of coordination in wireless sensor networks has been addressed for the first time in [Melodia'05]. In this work, the authors propose a framework that uses an event-driven clustering protocol to group sensor and actor nodes within the event area in the same group. Sensor and actor nodes are grouped inside the cluster in form of d-trees. Each tree connects a group of sensor nodes within the cluster to an actor node, where this actor node is the root of the d-tree. The main drawback of this approach is that it considers the case of multiple actors only. In the case where the event area is small, or when only one actor is needed, this framework becomes inefficient as it will need a coordination scheme between actor nodes.

In chapter 4 we proposed a new semantic clustering protocol for wireless sensor networks that groups nodes relevant to a user query in the same group. Cluster nodes are organized in a tree where the cluster head is the root. Data travelling from leaf nodes towards the cluster head are aggregated at each level of the tree in order to reduce the data amount and save energy. However this work can not be applied in wireless sensor and actor networks as it needs a user query to define the required information. In this chapter, we present a modification for the semantic clustering protocol proposed in chapter 4 by adapting it to wireless sensor and actor networks.

Our approach is to design a framework that allows sensor nodes within the event area to collaborate together and communicate with the same actor, by involving them within the same cluster and establish a path between the cluster head and the nearest actor to the event source.

7.2 A Coordination Framework for Single Actor Model

The aim of our framework is to fulfil the single actor model condition by informing one actor and only one actor if an event is detected.

In our framework, when an event is detected sensor nodes within the event area start exchanging their readings in order to find the node with the highest value and build a cluster around it. This node is elected as cluster head and becomes the routing point between all the cluster members and the nearest actor to the event source. In this section, we present in details the elements of our coordination framework.

We assume in the following that both sensor and actor nodes are location aware, where each location is reported by its X and Y coordinates, as the nodes can be equipped with a GPS receiver or the position can be determined by means of locations techniques [Hightower'01].

Our coordination framework consists of three stages:

- *Initial network organization*: This operation will occur at the initial network deployment and will allow each sensor node to find its nearest actor, by organizing the network in a Voronoi diagram, where each actor node builds its own Voronoi region that contains its nearest sensor nodes.

- *Cluster formation*: This operation occurs each time an event is detected and aims to group nodes within the event area in the same cluster, such as all those nodes' readings will be grouped at the cluster head.

- *Data dissemination*: This operation will follow the cluster formation immediately and aims to inform the nearest actor to the event source about the event.

7.2.1 Preliminary

The Voronoi diagram has been re-invented, used and studied in many domains. According to [Aurenhammer'00] the Voronoi diagram is a fundamental construct defined by a discrete set of points. In 2D, the Voronoi diagram of a set of discrete points partitions the plan into a set of convex polygons such that all points inside a polygon are closest to only one site. One can imagine a wireless sensor and actor network as a Voronoi diagram where each Voronoi region contains an actor and its nearest sensor nodes as it is illustrated in figure 7-1.

Such organization of the network helps sensor nodes to determine their nearest actor in case where an event is detected.

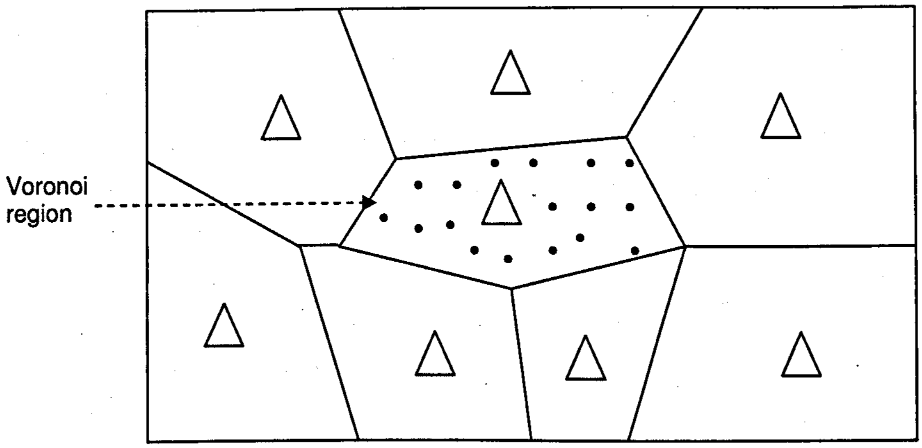


Figure 7-1: Voronoi organization of the network

Let *S* be the set of sensor nodes, *A* the set of actor nodes deployed in the network, and *d(a,s)* the distance separating the actor node *a* from the sensor node *s*.

For $a_1, a_2 \in A$ let $B(a_1,a_2) = \{x \in S \mid d(a_1,x) = d(a_2,x)\}$ be the bisector of a_1 and a_2.

Definition1

We call $B(a_1,a_2)$ the perpendicular line that separates the half-plane: $D(a_1,a_2) = \{x \in S \mid d(a_1,x) < d(a_2,x)\}$ containing a_1 from the half-plane $D(a_2,a_1)$ containing a_2.

Definition2

We call $V(a_1,A) = \bigcap_{a_2 \in A, a_2 \neq a_1} D(a_1,a_2)$ the Voronoi region of a_1 with respect to *A*.

Definition3

The Voronoi diagram of *A* is defined by $V(A) = \cup V(a_i)$.

In the next section, we will explain the algorithm that helps to organize the wireless sensor and actor network as Voronoi diagram.

7.2.2 Initial Network Organization

As mentioned before the fundamental aspect in wireless sensor and actor networks is to inform each sensor node about its nearest actor. Such information is really important, as the choice of the actor and the routing path depends on it. This phase is used to help sensor nodes to find their nearest actor and establish a routing path to it. As sensor nodes are resources limited and actor nodes are not, instead of solving this problem at sensor node level, we propose to solve it at the actor node level. In other terms, each actor finds out its nearest sensor nodes.

Once all sensor and actor nodes are deployed, each actor node starts broadcasting an *actor advertisement message* to its neighbour nodes. This message contains the node's id, its device function (sensor or actor), and its location. Meanwhile, sensor nodes enter a listening mode for a period of time *T*. In this listening period, each sensor node that receives an *actor advertisement message* for the first time, calculates its distance from the actor node mentioned in the message. As this message is the first actor advertisement received, the receiving sensor node considers the actor as its nearest actor, and set up a gradient towards the node from which it received the message. If the sensor node receives another *advertisement message* from another sensor node about the same actor it simply ignores it. This is because in this framework we consider the time constraint while defining the path towards the nearest actor. The aim of setting a gradient towards the sender node of the *advertisement message* is to establish the shortest path towards its nearest actor as illustrated in figure 7-2.

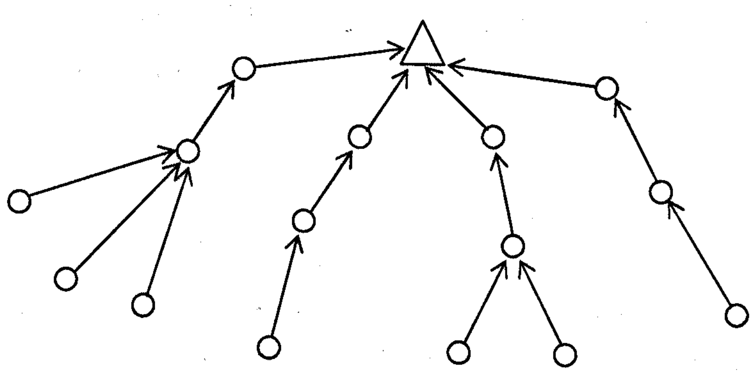


Figure 7-2: Shortest path tree within a Voronoi region

The sensor node broadcasts the message afterwards to its neighbours. If the sensor node receives another *advertisement message* from another actor before the listening period expires, it calculates its distance from the new actor node. If the new actor is closer to it than the previous one, the sensor node updates its information by considering the new actor as its nearest actor node, deleting the previous gradient and setting up a gradient towards the new sender sensor node of the *advertisement message*, before broadcasting the message to its neighbours. The algorithm used by sensor nodes to select the nearest cluster head is described in figure 7-3.

```
Nearest_actor=0;

Until listening period expires do

  Receive actor_adv_message;

   If(actor_adv_message.actor_id== Nearest_actor)
   Return;

  Distance_to_Actor=CalulateDistance (local_position, actor_adv_message .actor_position);


   If (Nearest_actor==0)
     Nearest_actor= actor_adv_message.actor_id;
     Set_up_gradient ( actor_adv_message.sender_id);
    Distance_to_Actor=CalulateDistance (local_position, actor_adv_message .actor_position);
   Else
      If (CalulateDistance (local_position, sender_position)< Distance_to_Actor)
        Nearest_actor= actor_adv_message.actor_id_id;
        Set_up_gradient ( actor_adv_message.sender_id);
       Distance_to_Actor=CalulateDistance (local_position, sender_position);
     End if
   End if
```

Figure 7-3: Nearest actor selection algorithm

At the end of this phase each node will have information about its nearest actor and the routing path to it. This routing path will be used to send the data towards the actor.

7.2.3 Event Detection and Cluster Formation

The aim of our work is to coordinate the communication between sensor nodes detecting the same event in order to inform only one actor at a time. In order to reduce the time delay, the chosen actor must be the nearest possible to the event source. According to the environmental model presented in chapter 2, the signal detected by a sensor node is inversely proportional to its distance from the source of the signal. Therefore, the nearest sensor node to the event source is the node with the highest reading. In order to achieve our goal, we propose a fully distributed semantic clustering algorithm that allows to group sensor nodes detecting the same event in the same cluster. In this algorithm the node with the highest reading is elected as cluster head.

When a sensor node detects an event it broadcasts an *event-detection* message to its neighbours and waits for other *event-detection* messages from its neighbour nodes for time interval T_{wait} . The event detection message must contain the sensor node id and the value of its detected signal. If a sensor node that detects the event receives an *event detection message* with a signal value exceeding its own value, before the T_{wait} timer has expired, it considers this node as its new parent node. If the received messages contains a signal value less than the node's local value, the node simply ignores the message. If the node receives more than one *event detection message* within the T_{wait} interval it considers the node with the highest reading as its new parent node. If a node that does not detect the event, receives an *event detection message* it simply ignores the message.

If a node detecting the event has not received any *event detection message* with a signal value exceeding its own value, until the T_{wait} timer has expired, it elects itself as cluster head. The distributed algorithm used to create the cluster and elect the cluster head is described in figure 7-4.

Note that unlike the initialization phase, in this phase sensor nodes do not broadcast the received messages again. This is because our aim in this phase is to determine the nearest sensor node to the event source and group sensor nodes within the event area around it, in a tree organization, where the cluster head is the root, as it is illustrated in figure 7-5.

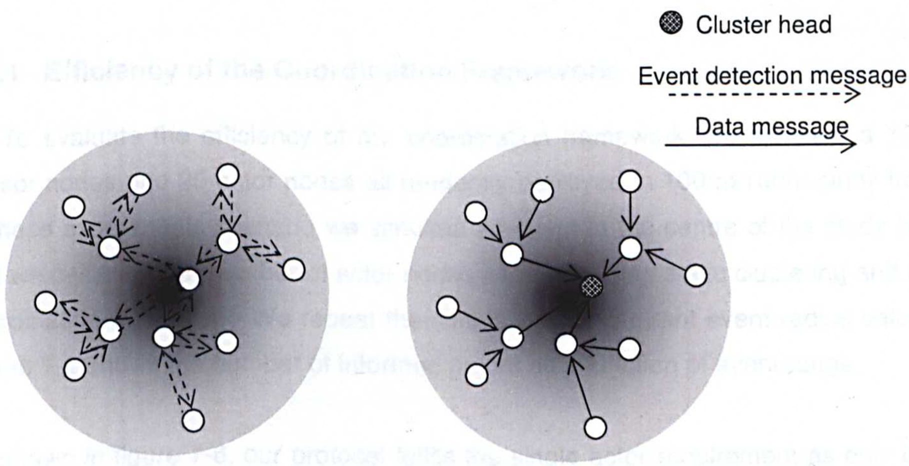
```
If(event detected)
   Broadcast event_detection_message;
   Max_Value=local_signal_value;
   Set Timer T_wait ;

   Until T_wait expires do
      Receive event_detection_message;

      If (event_detection_message.signal_value>Max_Value)
         Parent_node = event_detection_message. Sender_id;
         Max_Value   = event_detection_message.signal_value;
      End if
   End do

      If (Max_Value==local_signal_value)
         Cluster_head=true;
      End if
End if
```

Figure 7-4: Cluster formation and cluster head election algorithm



(a) Nodes exchange event detection messages
(b) Cluster members send their data towards the cluster

Figure 7-5: An example of cluster formation

At the end of the cluster formation process, each sensor node within the event area sends a data message to its parent node, containing the sensor node id, its location and its collected data. Each parent node that receives data from its children nodes performs an aggregation operation on the received data before sending the result to its parent node. This process is performed along the formed tree until the data reaches the cluster head. The cluster head uses the shortest path established in the initialization phase to send the collected information about the detected event to the actor.

7.3 Evaluation

We evaluate our coordination framework through simulation using the same simulator and with the same parameters presented in the chapter 3.

Our goal through these simulations is to assess the efficiency of our solution and evaluate its performance in terms of energy saving and time delay, and the impact of the actor nodes density on the framework performance. Due to the lack of similar works on this area, we evaluate our framework to static clustering scheme in which nodes within each Voronoi region form a cluster. The actor in each Voronoi region is elected as cluster head.

7.3.1 Efficiency of the Coordination Framework

To evaluate the efficiency of our coordination framework, we simulate a 1000 sensor nodes and 25 actor nodes all randomly deployed in 100mx100m study field. In these experiments scenario we simulate an event in the centre of the study field and we calculate the number of actor nodes informed using static clustering and our coordination framework. We repeat the simulation for different event radius values. Figure 7-6 shows the number of informed actors as a function of event range.

As shown in figure 7-6, our protocol fulfils the single actor requirement as only one actor is informed about the event, while in the static clustering protocol, the number of informed actors increases as the event radius increases. This has an impact on the energy consumption in the wireless sensor and actor networks. Thus, the static clustering protocol needs sophisticated algorithm for coordination between different actors.

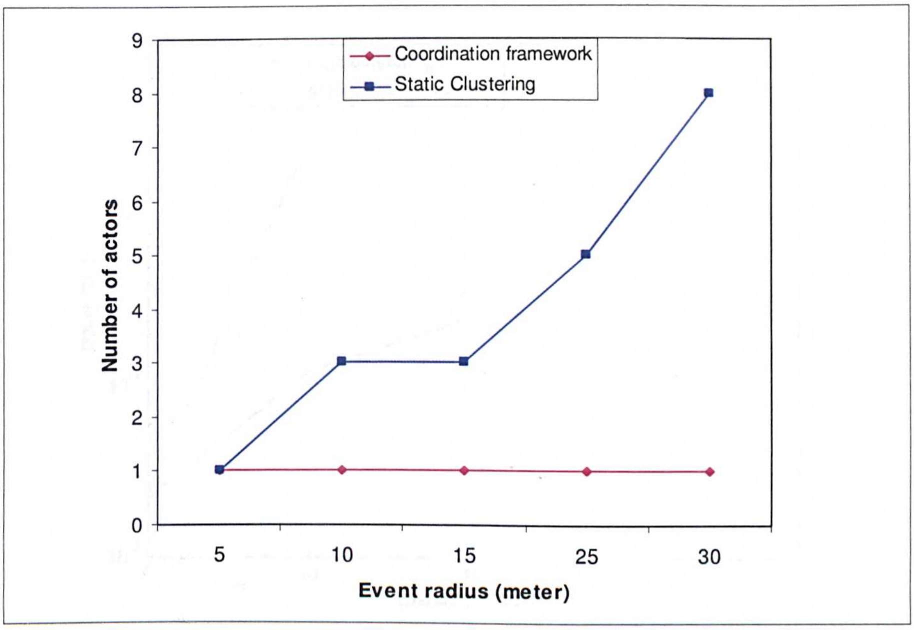


Figure 7-6: Number of informed actors over the event radius

We measure also the time delay necessary for sensor nodes to inform an actor, when the event is detected, for both static clustering and our coordination framework. The obtained time delay results are presented in table 7-1

Event Radius (meter)	Delay with Static Clustering (ms)	Delay with Coordination Framework (ms)
5	0.022	0.023
10	0.12	2.7
15	0.25	4
25	0.34	4.7

Table 7-1: Average time delay to inform an actor

Figure 7-7 shows the average delay necessary to inform an actor with static clustering and our coordination framework, for different event radius values.

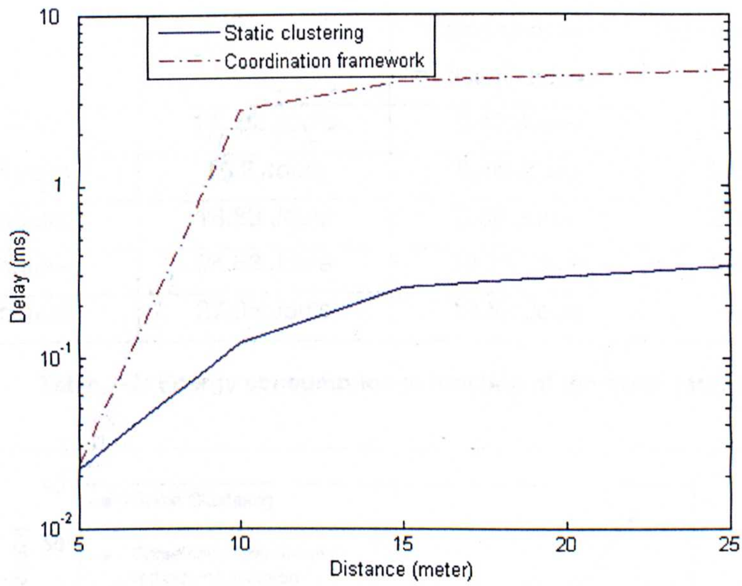


Figure 7-7: Average time delay to inform an actor node

As shown in figure 7-7, the static clustering approach achieves shorter time delay than our coordination framework. This is because in static clustering, sensor nodes that detect an event contact their respective nearest actors, while in semantic clustering, all sensor nodes need to send their readings to the cluster head's nearest actor even if it is far way from them.

To evaluate the energy cost of our coordination approach we measure the amount of energy consumed by the network to inform the actor when the event is detected, for both static clustering and our coordination framework. We repeat the simulation for different event radius values.

To show the cost of the initialization phase, we measure the energy consumed by our coordination framework with and without considering the initialization phase energy cost. The obtained results are presented in table 7-2 and in figure 7-8.

Event radius	Static clustering	Coordination framework with initialization	Coordination framework without initialization
5 meters	14. 02 Joule	9.42 Joule	0.19 Joule
10 meters	15.2 Joule	9.46 Joule	0.23 Joule
15 meters	18.83 Joule	9.68 Joule	0.45 Joule
25 meters	24.88 Joule	10.16 Joule	0.93 Joule
30 meters	37.08 Joule	10.63 Joule	1.4 Joule

Table 7-2: Energy consumption in function of the event radius

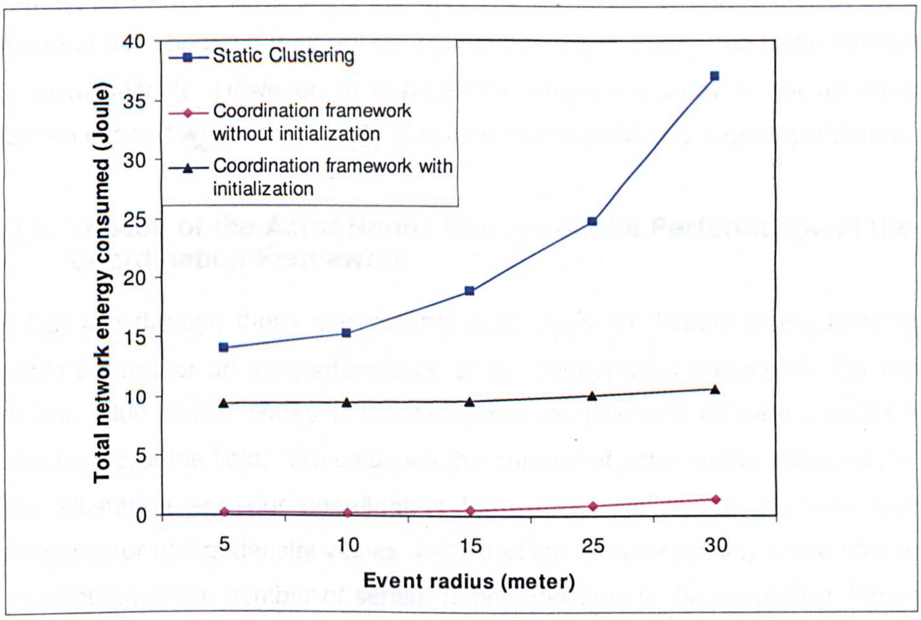


Figure 7-8: Energy consumption in function of the event radius

As shown in table 7-2 and figure 7-8, the energy consumption in the static clustering approach increases as the event range increases. This is because in static clustering, sensor nodes that detect the event belong to different clusters, and therefore inform their nearest actors, which results in too much traffic load and an increase in the energy consumption. We can see also that in the case of our framework the initialization phase is the most energy consuming operation. We can see also that the measured energy consumption without taking into consideration the initialization phase, does not exceed 1.5 Joule.

It is important to emphasize that the initialization phase is performed at the deployment time only, and therefore the energy consumed in this phase is considered only once. The obtained results show also that our coordination framework achieves simplicity as it does not require coordination between actor nodes by satisfying the single actor condition. It also achieves efficiency by saving more energy.

The obtained results show also the trade offs between the delay to inform an actor and the energy dissipation in both approaches. With our approach we can not inform the actor as fast as in the static approach. In applications where the actors need to informed as soon as an event is detected and where the energy is plenty, the delay exceed of our approach may not be acceptable and therefore the static approach is the more suitable. However, in applications where the delay is not an important requirement and where the energy is scarce, our approach is a good candidate.

7.3.2 Impact of the Actor Nodes Density on the Performance of the Coordination Framework

Our aim through these experiments is to study the impact of the actor nodes density parameter on the performance of our coordination framework. For that we simulate 1000 sensor nodes in 100mx100m study field and 15 meters radius event in the centre of the field. We calculate the number of actor nodes informed for both static clustering and our coordination framework. We repeat the simulation for different actor nodes density values. Note that the network density is represented as a percentage of the number of sensor nodes deployed in the simulation. Figure 7-9 shows the number of informed actor nodes using static clustering and our coordination framework for different actor nodes density values.

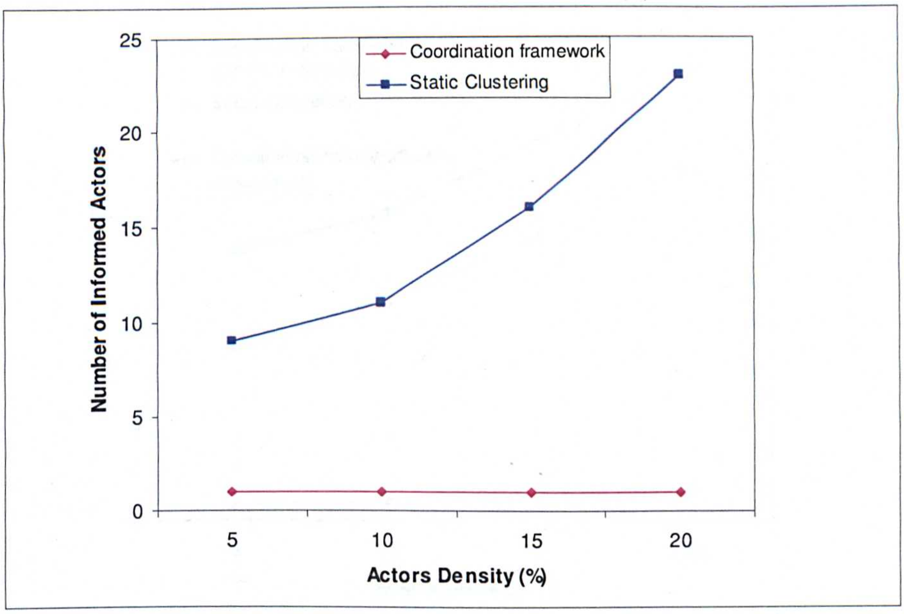


Figure 7-9: Number of informed actors over the actors' density

As shown in figure 7-9, the variation in the actor nodes density has an impact on the number of the informed actors in the static clustering since the number of informed actor nodes starts increasing as the actor nodes density increases; however a change in the actor nodes density has no influence on coordination framework.

We also measure the energy consumed by the network for the two approaches for different actor nodes density values. We measure the energy consumed by our coordination framework with and without considering the initialization phase energy cost. The obtained results are presented in table 7-3 and represented in figure 7-10.

Actors' density (%)	Static Clustering	Coordination framework with initialization	Coordination framework without initialization
5	13.82 Joule	8.92 Joule	0.74 Joule
10	15.69 Joule	11.15 Joule	0.95 Joule
15	19.43 Joule	14.52 Joule	1.03 Joule
20	22.79 Joule	18.06 Joule	1.5 Joule

Table 7-3: Energy consumption over the actors' density

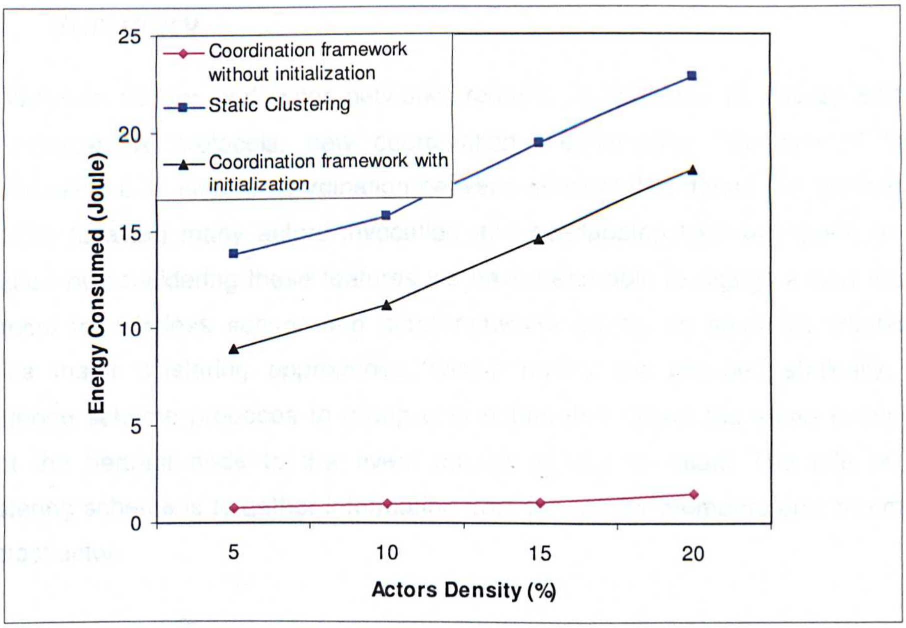


Figure 7-10: Energy consumption over the actors' density

The obtained results show that the energy consumption in static clustering increases as the actor density increases. These results are expected since the number of clusters in static clustering depends on the number of actor nodes, and therefore; when the number of actors increases the number of clusters increases, which results in an increases in the traffic amount and energy consumption.

These results show also that the initialization phase is sensitive to the actors' density. This is due mainly to the number of messages generated by actor nodes in this phase. An increase in the number of actors will result in an increase of messages in this phase. However, as mentioned this phase is performed only at the deployment time, and therefore its energy cost can be considered acceptable. As shown in figure 7-10, the energy consumed by our framework without taking into account the initialization phase, is very small. The obtained results prove that besides its simplicity, the semantic clustering used in our coordination framework is almost insensitive to the variation in the actors' density.

7.4 Summary

Wireless sensor and actor networks require, in additions to energy efficient communications protocols, new coordination mechanisms. The aim of these mechanisms is to ensure coordination between sensors that detect the same event in order to avoid many actors invocation and overlapping between them. In this chapter, by considering these features we have been able to design a new routing protocol for wireless sensor and actor networks based on semantic clustering. Unlike major clustering approaches, where nodes are grouped statically, our clustering scheme proposes to group only nodes that detect the same event and elect the nearest node to the event source as cluster head. The role of this clustering scheme is to gather information from the cluster members and inform the nearest actor.

Simulations showed that our clustering scheme satisfies the single actor condition. Thus, it achieves simplicity by avoiding the need for coordination mechanisms between different actors. Moreover, our coordination framework achieves much more energy saving than static clustering approach. The protocol also showed reasonable time delay performance that would satisfy a large number of applications. By investigating the coordination problem in wireless sensor and actor networks, we have the following conclusions:

- Wireless sensor and actor networks suffer from a lack of coordination between sensor nodes, besides the energy constraints already identified in wireless sensor networks.

- Wireless sensor and actor networks suffer also from a lack of coordination between sensor nodes and actor nodes, as sensor nodes are generally not aware about the position of actor nodes, and therefore they can not communicate with them directly.

- An ideal routing protocol must allow communication between sensor nodes that detect the same event, and also between those sensor nodes and actor nodes, while saving the network resources.

- Semantic clustering is a suitable candidate for wireless sensor and actor networks, however; it needs an initial organization of the network that allows sensor nodes to establish communication paths with their nearest actor nodes.

8 Conclusions and Future Work

This thesis has presented new communication mechanisms for wireless sensor networks based on semantic clustering. A number of novel schemes and protocols have been developed and presented. The new semantic clustering mechanisms aim to provide a set of communication protocols for wireless sensor network applications that can offer an efficient data delivery to the user while saving the network scarce resources as much as possible.

This chapter is organized as follows: Section 8.1 presents summary of the thesis. Our main contributions, the semantic clustering mechanisms and the new set of protocols are presented in section 8.2. Future work is investigated and proposed in section 8.3, and conclusions are provided in section 8.4.

8.1 Thesis Summary

Wireless sensor networks are the results of the advance made in wireless channel technology and micro-electro-mechanical systems design. These networks are expected to enable exciting applications, and to help the user to extract data remotely from different environment. While these networks are cheap and very easy to deploy, they add constraints that are not found in traditional networks. Specifically, the wireless channel is bandwidth limited and the sensor nodes are typically battery-operated and hence energy constrained. In addition, sensor nodes are densely deployed and consequently generate huge amount of low level description data, while the user is interested only in specific small amount of high level description and accurate data. Therefore, it is important to design new protocols and algorithms for wireless networks to be resource efficient as well as aware about the user requirements.

Our work focuses on the design of communication protocols that can provide a high description of the monitored environment, and take into account the resources constraints of the wireless sensor network. To achieve this goal we have developed several schemes in the area of routing and data dissemination in wireless sensor networks.

Chapter 1 outlined the main characteristics of wireless sensor networks as:

1) Limitation of resources such as energy, bandwidth, memory and computation power.

2) A dense deployment of sensor nodes and a high correlation of the retrieved data.

3) A lack of global identification and a random deployment of sensor nodes

These characteristics make the design of a routing protocol for such kind of network difficult. At one hand, the routing protocol must satisfy the user requirement and deliver a high level description information to the user, and at the other hand this protocol must be the most resources efficient possible.

Chapter 2 presented a survey of actual communication protocols and research projects on wireless sensor networks as well as a state of art on routing protocols for wireless sensor networks found in the literature. This chapter pointed the main drawbacks of existing works and the issues that need to be addressed as:

1) Existing routing protocols are either too much focused on the user data interest and only consider the resources issue as a second priority like in

data-centric routing protocols, or consider the resource constraint as a priority but neglect the user requirements.

2) Major works on routing in mobile event monitoring application are not energy efficient and emphasize the necessity to re-study this issue.

3) The coordination problem in wireless sensor and actor networks has not been addressed yet although it is a crucial element to the success of these networks.

Chapter 3 explained in more details the mentioned issues and presented our approach to tackle these important challenges by describing the novel contributions that compose our work.

Our novel contributions were explained in details in the chapters 4, 5, 6 and 7. We present the analysis of the problem, the design, the evaluation of the suggested schemes in each chapter.

Chapter 4 provided a description of our semantic clustering routing protocol with its different phases. This protocol has been evaluated through simulations and compared to existing routing protocols.

Chapter 5 presented an overview on our clustering protocol for mobile event monitoring applications in wireless sensor networks. The different elements of this protocol have been described with details in this chapter. We evaluated our clustering protocol in chapter 5 through simulations and outlined its advantages over existing schemes.

In chapter 6, we presented our node recovery scheme for data dissemination in wireless sensor networks. In this chapter, we described with details the different parts of this scheme and we studied the different factors that influence its performance. We used analytical analysis and simulations to evaluate this work and we compared it with existing data dissemination solutions.

Finally in chapter 7, we addressed the problem of coordination in wireless sensor and actor networks and we described the single actor model issue. In this chapter we provided an overview of our coordination framework for the single actor model in wireless sensor and actor networks. We described in details the different elements of this framework. We evaluated this framework through simulations and proved that it satisfies the single actor model condition while achieving good energy saving and time delay.

8.2 Research Contributions

When designing communication protocols for wireless sensor networks, it is important to clearly define the goals and requirements of such systems. This will enable the designer to make good tradeoffs in the different system parameters to best support wireless sensor networks applications. Based on the design constraints we developed semantic clustering communication mechanisms that provide large benefits to the application. These mechanisms are based upon the following schemes developed as parts of our contributions:

- We have proposed a new semantic clustering routing protocol for wireless sensor networks [Bouhafs'06-a]. The proposed protocol ensures that only sensor nodes that satisfy a user query are grouped in the same cluster and that the data sensed by these nodes is gathered in an energy efficient way. This protocol takes advantages of both data centric routing protocols and hierarchical clustering protocol by considering both the user interest and the energy constraints of wireless sensor networks. The protocol also avoids flooding the network with interest messages by using a new query dissemination scheme that reduces the number of interest messages propagated in the network. It also avoids the cluster head overload problem by proposing a tree organization of the cluster members, allowing a layered data aggregation and distributed energy dissipation.

- We have proposed an energy efficient clustering protocol for mobile event applications in wireless sensor networks [Bouhafs'06-e]. The proposed protocol uses the semantic clustering protocol to group sensor nodes detecting the tracked event. To update the cluster when the event is moving, our protocol proposed a cluster membership update mechanism that allows sensor nodes to join or leave the cluster, and even re-elect new cluster head according to sensor nodes detected signal. This cluster membership scheme avoids re-building a new cluster each time the tracked object changes position and thus saves more energy and extends the network lifetime. This advantage of the cluster membership update scheme is significantly important in the case of highly mobile objects. Moreover, as event may split into two or more new sub-events, the presented protocol provides a cluster split scheme that allows the user to monitor the event split and the resulting new events.

- We have presented a node recovery scheme that helps to provide a robust and energy efficient data dissemination to the wireless sensor networks applications [Bouhafs'06-e]. This node recovery scheme helps to replace energy-exhausted nodes with other neighbouring nodes and extends the routing path lifetime, and thus offers a better network connectivity. The proposed recovery scheme works in conjunction with any gradient-based single path routing protocol and exploits the density characteristic of wireless sensor networks and the broadcasting nature of the wireless medium.

- We have addressed the problem of coordination in wireless sensor and actor networks by proposing a coordination framework for the single actor model in wireless sensor actor networks [Bouhafs'06-c, Bouhafs'06-d]. The proposed framework organizes the sensor and actor nodes in Voronoi regions where each region contains a single actor and its nearest sensor nodes. Such organization allows each sensor node to know its nearest actor and establish a routing path to it. This framework uses the semantic clustering concept to group nodes that detect a certain event in the study field. This grouping is useful to allow these sensor nodes to work in a collaborative way in order elect the best actor to contact. The proposed framework, thus, guarantees that only one actor is contacted if an event is detected in the study field.

8.3 Comparison with Existing Works

As mentioned before, the main objective of our communication mechanisms is to provide a set of routing protocols and communication schemes that allow the user to collect the desired information from the sensor field at minimum energy cost and with the shortest time delay. The problem of routing in wireless sensor networks has been treated by many research groups, and many routing protocols have been proposed. Our work shares some similarities with prior works carried out in other projects. In this section we compare our mechanisms with these works.

The protocol Directed Diffusion proposed in [Intanagonwiwat'03] is a data centric routing developed to look for sensor nodes satisfying a user query. Once found these sensor nodes start sending information to the user through different paths. However, the semantic clustering routing protocol proposed in our work is more energy efficient than Directed Diffusion. Indeed, the simulations performed in this work show that the query dissemination proposed in our routing protocol is more energy efficient as it avoids flooding and reduces the scope of the interest propagation. Moreover, our routing protocol reduces the number of data messages by grouping nodes in a cluster and aggregating their data and thus saves more energy.

The protocol LEACH proposed in [Heinzelman'02] is also a routing protocol that uses clustering and data aggregation to reduce amount of data sent to the user and save energy resources. Our semantic clustering protocol, however; has many novel aspects and present several advantages over LEACH protocol. First, our semantic clustering protocol guarantees that only nodes satisfying the user query or detecting the same specific event are grouped in the same cluster, their data are aggregated and transferred to the user. Second, the clustering operation uses, besides the neighbouring information, the relevancy of sensor nodes to the user query and thus our protocol achieves better data quality and accuracy than LEACH. Third, the nodes within the cluster are organized in from of tree where the cluster head is the root. Using this tree organization, data travels from level to level in the tree allowing a layered a data aggregation and reduces the amount of data more than in LEACH. Finally, the tree formation guarantees a balanced energy dissipation and avoids the cluster head overload and re-election, which helps to maintain the connectivity between cluster members and to extend the network lifetime much longer.

Our solutions share also some similarities with other works developed in the area of mobile event monitoring. In [Chen'04] a clustering based acoustic target tracking protocol is proposed, where nodes detecting a tracked object are grouped in a cluster and send their readings to the cluster head. When the object changes its position, a new cluster is formed around it, while in our mobile event monitoring protocol we propose to update the membership of the original cluster. The evaluation of two protocols shows that the approach proposed in [Chen'04] is more energy efficient in case where the tracked event is moving at low speed. However, when the event is moving at high, the evaluation shows that our approach is more energy efficient than the approach proposed in [Chen'04]. In addition, the cluster split proposed in our work presents a significant advantage over existing event monitoring approaches as they do not treat the issue of event split in wireless sensor networks.

Considering the problem of data dissemination in wireless sensor networks, our work presents also some advantages over existing approaches [Huang'05, Xu'01] which are either based on single path approach or multipath approach. Simulations shows that the node recovery scheme presented in our work maintains the network connectivity and extends the network lifetime much longer than major single path based solutions like the works proposed in [Barrett'03]. Moreover, our scheme maintains the network connectivity much longer than multipath based approaches while performing better energy saving and network lifetime extension.

The mechanisms proposed in this thesis contribute to our understanding of the benefits of designing communication protocols that consider the application profile, the user requirements, and the network constraints. We have developed and evaluated these communication mechanisms for wireless sensor networks based on semantic clustering. These mechanisms are better able to support wireless sensor networks applications than other communication approaches and protocols for wireless sensor networks.

8.4 Future Work

For future research, we plan to extend this work in several directions. The first is to make the semantic clustering protocol fault tolerant and adapt it to hostile environments where sensor nodes are more exposed to failure. The second challenge is to consider routing in mobile wireless sensor networks by adapting our semantic clustering protocol to situations where sensor nodes are mobile and deployed to track a mobile event in the environment. The third challenge is to design and implement a synchronization scheme for sensor nodes within a cluster.

- ***Fault Tolerance:*** The semantic clustering routing protocol suggested in this work assumes that energy exhaustion is the only cause of sensor nodes failure. However, sensor nodes can sometimes be deployed in hostile environment where nodes are more exposed to hardware failure, such as in the case of battlefield applications. Therefore, it is necessary to adapt our semantic clustering protocol to such harsh conditions and make it fault tolerant. The most difficult issue regarding fault tolerance in our semantic clustering protocol is how to maintain the tree organization within the cluster in the case where some parent nodes or the cluster head fail. In addition to the tree maintenance, data dissemination path maintenance needs to be considered as well. Indeed, although we proposed a node recovery scheme for data dissemination in wireless sensor networks, this scheme may not be efficient enough in the case where the rate of nodes failure is high. To tackle this problem it is important to take fault tolerance into consideration at the design level of the semantic clustering protocol. For instance, it is essential to save some paths between the sink and the sensor nodes within event area that have been generated in the interest propagation phase. Another example that may help to make our protocol fault tolerant is to store some or all the cluster head candidates' *ids* in the case where the cluster head fails. To achieve that, a network management protocol is needed to inform sensor nodes about the failure rate in the network and to provide them the necessary data to maintain the cluster and the routing path.

- ***Routing for Mobile Wireless Sensor Networks:*** Even though we assumed in this research that the wireless sensor network is static, it is possible to have mobile sensor nodes [Rahimi'03]. In mobile wireless sensor networks, nodes move freely to get necessary information about a certain event that moves in the nature, such as toxic gas cloud or a radioactive mobile object, etc. In mobile wireless sensor networks applications, the user is also interest in high level description information about the tracked event, and therefore semantic clustering and data aggregation techniques are needed to retrieved the required information and delivered it to the user. However, the main problem with mobile wireless sensor networks is that the sensor node movement is dependant upon the changes in the sensor's readings. For instance, in the case of a radioactive mobile object monitoring applications, a sensor node moves always towards the region where the radioactivity is higher. Moreover, a mobile sensor node can not always relay on its own reading to detect the event, but it needs also to consider other nodes with which it can communicate as its mobile extended sensors. At the same time, some environmental effects such as lack of GPS signal or loss of line-of-sight between sensor nodes may hinder the wireless sensor network ability. All these factors render adapting the semantic clustering routing protocol for this kind of networks very challenging.

- ***Synchronized Communication Scheme:*** One of the main factors that may affect the performances of our semantic clustering scheme is the synchronization of the communication between sensor nodes. Indeed, as our semantic clustering protocol allows a layered data aggregation it is important that all parent nodes receive the data messages from all their children nodes before performing the data aggregation and sending the results to the upper layer. Therefore, each parent node needs to specify a transmission schedule for its children nodes so that it can receive the data messages at a specified time and aggregate it. At the same time, each parent node must respect the schedule set by its own parent node in the tree and, thus; it needs to send the data aggregation results at a specific time as well. Moreover, the issues related to network density and the high probability of collision in this kind of networks, render the problem of synchronized communication more challenging. Consequently, a new synchronized communication scheme for wireless sensor networks is needed. This scheme will have the task of synchronizing the communication between the nodes from different levels in the tree formed within the cluster. This scheme must also guarantee that sensor nodes from the same level of the tree fairly share the wireless medium.

8.5 Concluding Remarks

Recent advances in micro-electro-mechanical systems, digital electronics and wireless communications have enabled the development of low-cost, low-power, multifunctional sensor devices. Researchers, riding on in this advance, expect that wireless sensor networks will become smaller, cheaper and thus deployed in large number. By distributing sensors spatially, the wireless sensor network could provide better coverage, faster response to dynamically changing environments, better survivability, and robustness to failure. However, these networks suffer from resource constraints that do not appear in more traditional wire networks. Moreover, the huge amount of data generated by sensor nodes due to their dense deployment, along with the lack of global identification system, make communication in this kind of networks very challenging. On the hand, the users of wireless sensor networks are, generally, interested in monitoring physical events that occur in the monitored environment, and require high level description information from the sensor nodes, rather than their individual readings.

Therefore, new communication protocols are needed to tackle these resources constraints and satisfy the wireless sensor networks user requirements. In this thesis, we highlighted the main problems and challenges to design communication protocols for wireless sensor networks, and then we presented our approach for dealing with these problems.

Our solution is composed of new communication mechanisms based on semantic clustering that consists of four novel communication schemes, designed to support routing in wireless sensor networks: (1) a new semantic clustering routing protocol for wireless sensor networks [Bouhafs'05, Bouhafs'06-a, Bouhafs'06-d], (2) a new energy-efficient mobile event monitoring protocol in wireless sensor networks [Bouhafs'06-c], (3) a node recovery scheme for data dissemination in wireless sensor networks [Bouhafs'06-e], and (4) a coordination framework for single actor model in wireless sensor and actor networks [Bouhafs'06-b, Bouhafs'06-c].

We analyzed and evaluated the proposed schemes analytically and by simulation techniques. Our evaluation was focused on the three important parameters of wireless sensor networks, namely, network lifetime, time delay and data accuracy. By comparing our results to those of other mechanisms available on literature, we showed that our solution is more energy efficient than other approaches, and extends the network lifetime much longer. We showed also that our solution allows grouping nodes that satisfy the user query or detecting a same specific event. Our solution helps also to retrieve accurate date continuously from the environment even if the monitored event is moving or has split. The experiments showed also that our solution achieves very short time delays and this for different applications scenarios.

It is important to emphasize that though the proposed communication mechanisms were developed on some assumption about the environmental and radio energy models and applications profiles, the ideas carried by this work are still applicable for others models and applications profiles.

Appendix A

In this appendix we explain how we calculated the area R_{Max} presented in chapter 6, section 6.2, and illustrated in figure 1.

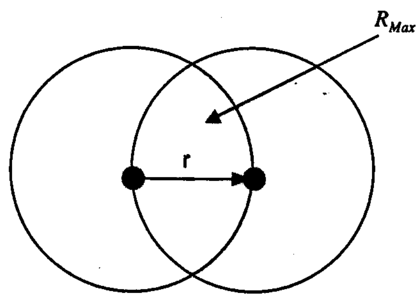


Figure 1

Figure 2 shows how to represent the area R_{Max} in the Euclidean plane.

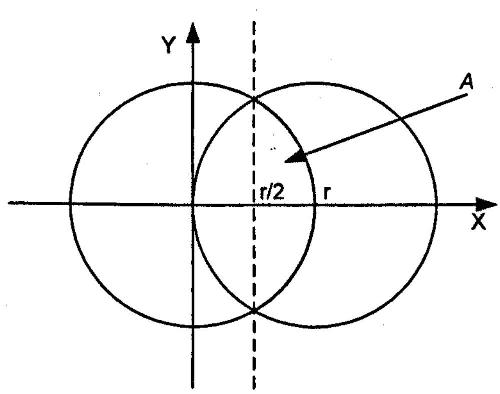


Figure 2

As shown in figure 2, the area R_{Max} represents four times the area *A* represented in the same figure. Therefore, it is possible to obtain the equation of R_{Max} by calculating the equation of the area *A*.

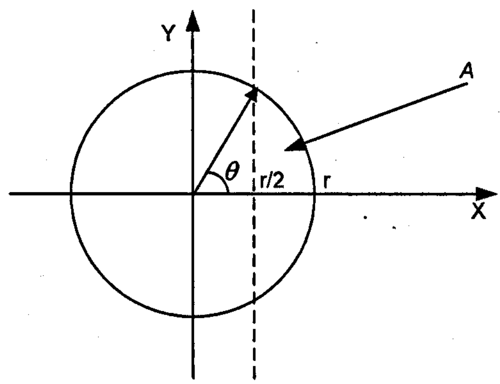


Figure 3

The circle represented in figure 3 is denoted by the following equation:

$$\frac{x^2}{r^2}+\frac{y^2}{r^2}=1$$

Solving the equation (1) for y, the following is derived:

$$y=\pm\sqrt{r^2-x^2}$$

The area A can be calculated by as following:

$$A=\int_{\frac{r}{2}}^{r}\sqrt{r^2-x^2}\,dx$$

To evaluate this integral we substitute $x=r\sin\theta$, and thus, the equation of the area *A* becomes:

$$A=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\sqrt{r^2-r\sin^2\theta}\,r\cos\theta d\theta=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\sqrt{r^2(1-\sin^2\theta)}\,r\cos\theta d\theta=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\sqrt{r^2(\cos^2\theta)}\,r\cos\theta d\theta$$

$$=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}r\cos\theta.r\cos\theta d\theta=\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}r^2\cos^2\theta d\theta=r^2\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}\frac{1}{2}(1+\cos2\theta)d\theta$$

$$=\frac{r^2}{2}\int_{\frac{\pi}{6}}^{\frac{\pi}{2}}(1+\cos2\theta)d\theta=\frac{r^2}{2}\left[\theta+\frac{1}{2}\sin2\theta\right]_{\frac{\pi}{6}}^{\frac{\pi}{2}}=\frac{r^2}{2}\left[(\frac{\pi}{2}+0)-(\frac{\pi}{6}+\frac{\sqrt{3}}{4})\right]$$

$$=\frac{r^2}{2}(\frac{\pi}{3}-\frac{\sqrt{3}}{4})=\frac{r^2}{2}.\frac{(4\pi-3\sqrt{3})}{12}$$

Thus we can calculate R_{Max} as following:

$$R_{Max}=4.A=\frac{r^2(4\pi-3\sqrt{3})}{6}$$

Appendix B

F. Bouhafs, M. Merabti, and H. Mokhtar. *"A Semantic Clustering Scheme for Wireless Sensor Networks"*, in the sixth annual postgraduate symposium on the convergence of telecommunications, networking and broadcasting, Liverpool John Moores University, 27-28 June 2005.

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F. Bouhafs, M. Merabti, and H. Mokhtar, *"A Coordination Framework for the Single Actor Model in Wireless Sensor and Actor Networks"*, Technical Report Submitted to Elsevier Wireless Communications and Mobile Computing, December 2006

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