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Routing in Wireless Sensor Networks: an Ant-inspired approach

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# Routing in Wireless Sensor Networks: an Ant-inspired approach

by

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Faculty of Graduate and Postdoctoral Studies

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## Abstract

The field of routing and sensor networking is an important and challenging research area of network computing today. Advancements in wireless sensor networks (WSNs) enable a wide range of environmental monitoring and object tracking applications. Routing in WSN is a challenging task. As the size of the network increases, routing becomes more complex. Therefore, biologically-inspired intelligent algorithms have been taken into consideration to address this problem. Ant routing algorithms have shown excellent performance when applied to WSN routing. This thesis presents routing algorithms in WSN, the current use of swarm intelligence for routing in WSN, explains different ant routing algorithms and shows why some existing ant routing algorithms do not work well for WSN. Consequently, we present four ant-colony based routing algorithms, which are suitable for WSN. Our proposed algorithms take into consideration the WSN requirements, including energy consumption, success rate, and time delay. In addition, one of our algorithms is a multimedia-enabled routing algorithm, which is suitable for single-source-to-single-destination multimedia data traffic to optimize different performance criteria, especially end-to-end delay and jitter. The last proposed algorithm is a many-to-one routing algorithm, which facilitates congestion avoidance in the network. The findings in this thesis are supported with several computer simulations.

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*To My Beloved Parents*

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# Acronyms and Abbreviations

<b>ACO</b>	Ant Colony Optimization
<b>ADR</b>	Adaptive Ant-Based Dynamic Routing
<b>AR</b>	Adaptive Routing
<b>Basic</b>	Basic Ant Routing
<b>BF</b>	Bellman-Ford
<b>BIIA</b>	Biologically-inspired intelligent algorithms
<b>BS</b>	Base Station
<b>CN</b>	Communication Network
<b>DARPA</b>	Defense Advanced Research Projects Agency
<b>DSN</b>	Distributed Sensor Network
<b>FF</b>	Flooded Forward Ant Routing
<b>FP</b>	Flooded Piggybacked Ant Routing
<b>GAF</b>	Geographic Adaptive Fidelity
<b>IAR</b>	Improved Adaptive Routing
<b>LEACH</b>	Low-Energy Adaptive Clustering Hierarchy

<b>M-AR</b>	Multimedia-enabled Improved Adaptive Routing
<b>MANet</b>	Mobile Adhoc Network
<b>MO-AR</b>	Many-to-One Improved Adaptive Routing
<b>OSPF</b>	Open Shortest Path First
<b>PQ-R</b>	Predictive Q-Routing
<b>PSO</b>	Particle Swarm Optimization
<b>Q-R</b>	Q-Routing
<b>QoS</b>	Quality of Service
<b>SC</b>	Sensor-driven Cost-aware Ant Routing
<b>SN</b>	Sensor Network
<b>SNR</b>	Sensor Network Routing
<b>SPF</b>	Shortest Path First
<b>SOSUS</b>	Sound Surveillance System
<b>SPIN</b>	Sensor protocols for information via negotiation
<b>TSP</b>	Traveling Salesman Problem
<b>WSN</b>	Wireless Sensor Network
<b>WSNR</b>	Wireless Sensor Network Routing

# Chapter 1

## INTRODUCTION

In this chapter, we present the objective and motivation for the current research. After that, we address some of the challenges in the research pertaining to ant routing algorithms. The thesis contribution, the publications resulting from this thesis, and the overall organization are illustrated subsequently.

### 1.1 Objective and Motivation

The objective of this research is to investigate the properties of a type of swarm intelligence commonly referred to as ant algorithms, and to come up with new ant routing algorithms that are applicable to wireless sensor networks (WSNs). Ant-inspired algorithms have the capability of finding short paths and show an inherent adaptability that could be utilized to solve dynamic problems such as routing in a network. Swarm intelligence is an area of research that has recently experienced a boom in interest. Inspired

by the intelligent behavior of swarms of insects, swarm intelligence has confirmed to be a promising field of research in many different areas. A swarm of ants in the search for food demonstrates a remarkable potential of finding shortest paths between the anthill and a found food source. Although any single ant could be said to possess the ability of finding a short path from the anthill to a near food source, the probability of this occurring is very small, due to its limited intelligence. Nevertheless, when many ants cooperate on finding food, using pheromone trails as a simple indirect form of communication, the swarm of ants seems to be able to find a shortest path effectively. Another characteristic is their capability to adapt to a changing environment. If an obstacle is located on the path from the food source back to the anthill, ants are able of finding the shortest path around the obstacle, and possibly find food sources nearer to the anthill. The emergent intelligence that a swarm of ants possesses is attractive from an artificial intelligence perspective as it can be exploited to solve several engineering problems. Indeed, researchers in the field of biology have developed interesting theories on how ants communicate as a group. Attempts to test these theories with computer simulations proved that it is possible to achieve emergent intelligent behavior from colonies of artificial ants [8].

## **1.2 The Research Problem**

Wireless sensor network routing (WSNR) is a potential research field of swarm intelligence. The quality of a routing algorithm could be measured by how fast the algorithm is capable to transfer packages through the network while visiting the least number of

sensor nodes, minimizing package loss, being energy efficient, and consuming the least energy. In [16], the authors show an adaptive distributed, mobile agent-based system, which is inspired from the ant colony metaphor for solving optimization problems and targeted for communication networks. Although their basic ant routing (Basic) algorithm forms the basic foundation of the research presented in this thesis, it is not optimized for routing in WSNs.

Zhang et al. [103] proposed three ant-routing algorithms for sensor networks: the Sensor-driven Cost-aware Ant Routing (SC) algorithm, the Flooded Forward Ant Routing (FF) algorithm, and the Flooded Piggybacked Ant Routing (FP) algorithm. The SC algorithm is energy efficient but suffers from a low success rate. The FF algorithm has shorter time delays; however, the algorithm creates a significant amount of traffic. Despite the high success rate shown by the FP algorithm, it is not energy efficient. Although all three algorithms show satisfactory performance, none of them is ideal for routing in WSNs due to the above-mentioned shortcomings.

An Adaptive ant-based Dynamic Routing (ADR) algorithm using a novel variation of reinforcement learning was proposed by Lu et al. [57]. The authors used a delay parameter in the queues to estimate a reinforcement learning factor. Although the queue is an integral part for a communication network, it is not essential in a sensor network.

Lu et al. [57] conducted a comparison study between ADR and AntNet in communication networks. The results showed that ADR is advantageous to AntNet. Zhang et al. [103] used AntNet as a reference for their developed algorithms. We expected that by using ADR for sensor networks and as a reference, we could propose an algorithm,

which gives better results than the ones previously presented in the literature. First we compare the results of the proposed Adaptive Routing (AR) algorithm and the proposed Improved Adaptive Routing (IAR) algorithm with the Basic, SC, FF, and FP algorithm. By comparing the results of all algorithms, the result showed that IAR has more advantages than Basic, SC, FF, FP and AR algorithms, which will be explain in chapters 4 and 5.

Because of the physical constraints of sensor nodes and the type of network topology used, many WSNs use multi-hop routing algorithms to achieve energy efficiency. A huge number of applications such as remote surveillance require that multi-modal sensory data be sent to a base station, which we refer to many-to-one type of communication. For example, capturing three views of a particular object and sending them to the base station will provide more accurate idea about the remote object than that provided by a single source. However, as the density of sensor nodes increases significantly, many-to-one type of communication in a multi-hop WSN generates high traffic and results in greater energy waste, higher end-to-end delay and packet loss. In order to accommodate these challenges, we propose a many-to-one routing algorithm using ant-based swarm intelligence to find the shortest path and to avoid congestion in the network.

### **1.3 Thesis Contributions**

The thesis proposes four swarm-intelligence-based algorithms to address the routing problem in WSNs. They are the Adaptive Routing (AR) algorithm, the Improved Adaptive

Routing (IAR) algorithm [32], the Multimedia-enabled Improved Adaptive Routing (M-IAR) algorithm [71] and the Many-to-One Improved Adaptive Routing (MO-IAR) algorithm [31].

The AR and IAR algorithms were designed to be optimal for transferring packets through the network, which results in less energy consumption, better packet success rate, and less latency in a WSN.

The M-IAR algorithm best fits for single-source-to-single-destination multimedia data traffic to optimize different performance criteria, especially end-to-end delay and jitter.

The MO-IAR algorithm is suitable for many-to-one sensory data transmission in a multi-hop WSN. By avoiding congestion, it can route the upstream data flow through the shortest path efficiently.

## **1.4 Publications Resulting from This Research**

Parts of this research have been published in the following papers:

- Reza GhasemAghaei, Md. Abdur Rahman, Wail Gueaieb, and Abdulmotaleb El Saddik. Ant Colony-Based Reinforcement Learning Algorithm for Routing in Wireless Sensor Networks. In Proceedings of the IEEE Instrumentation and Measurement Technology Conference (IMTC2007), Warsaw, Poland, May 1–3 2007.
- Md. Abdur Rahman, Reza GhasemAghaei, Abdulmotaleb El Saddik, and Wail Gueaieb. M-IAR: Biologically Inspired Routing Protocol for Wireless Multimedia Sensor Networks. IEEE International Instrumentation and Measurement Tech-

nology Conference (I2MTC2008), Victoria, Vancouver Island, British Columbia, Canada, May 12–15 2008.

- Reza GhasemAghaei, ASM Mahfujur Rahman, Md. Abdur Rahman, Wail Gueaieb, and Abdulmotaleb El Saddik. Ant Colony-Based Many-to-One Sensory Data Routing in Wireless Sensor Networks. In Proceedings of the ACS/IEEE International Workshop on Wireless Internet Services (WISE'08), Doha, Qatar, April 1–4 2008.

## 1.5 Organization of the Thesis

The remainder of the thesis is organized as follows:

**Chapter 2** provides background information related to this thesis, an overview of sensor network routing and describes some of the related protocols in this field.

**Chapter 3** introduces ant-inspired systems as well as different swarm intelligence approaches. Relevant literature is also discussed.

**Chapter 4** provides an overview of the four proposed adaptive routing (AR), improved adaptive routing (IAR), Multimedia-enabled Improved Adaptive Routing (M-IAR) and Many-to-One Improved Adaptive Routing (MO-IAR) algorithms.

**Chapter 5** demonstrates the performance of all routing algorithms in sensor networks with uniform and random node layouts.

**Chapter 6** summarizes and concludes the thesis with some concluding remarks and possible future research directions.

# Chapter 2

## THE STATE OF THE ART

In this chapter sensor networks will be introduced. Literature review on routing protocols and approaches will also be detailed.

### 2.1 Sensor Networks

Communication is the transfer of information from one device to another [26]. Since the 1970s, wireless networks have been showing huge interest to the computing industry and the research community. The last two decades have been the most active years in the history of wireless communications [23]. This is particularly true within the past decade, which has seen wireless networks being adopted to enable mobility [39, 72].

Recently, advances in minimization, low-power, low-cost, efficient and multi-functional wireless communication equipments, and improved small-scale energy supplies led to the increasing popularity of wireless sensor networks (WSNs) [2, 3, 46, 53, 75, 88]. Early sen-

sensor networks were applied for military purposes, such as the Sound Surveillance System (SOSUS) during the Cold War. Modern research on sensor networks started around 1980 with the Distributed Sensor Network (DSN) program at the Defense Advanced Research Projects Agency (DARPA). Smaller computing chips, more capable sensors, wireless networks, and other new IT technologies are pushing the development of sensor networks. Sensor networks are collection of small but smart low-cost devices that can sense and motivate their environment and communicate with each other through a wireless network. WSNs contain a large number of sensor nodes with sensing capabilities such as vibration, temperature, radiation, light, sound, pressure, motion, pollutants etc. and have simple wireless communication capabilities. They are deployed for a wide variety of areas, such as environment monitoring [19, 22, 27, 98], video surveillance, medical application, air traffic control, robotic exploration, manufacturing and industrial automation, and military and national security applications [10, 13, 33, 41, 69, 96].

Networking unattended sensor nodes is anticipated to have large impact on the effectiveness of many military and civil applications such as battle field surveillance, security and disaster management. These systems process data collection from many sensors to monitor events in an area of interest. For instance, a large number of sensors can be distributed in a disaster management setup. Networking these sensors can help rescue operations by locating survivors, identifying unsafe areas and making the rescue team more aware of the overall situation. Such application of sensor networks can raise the effectiveness of rescue operations, and enhance the safety of the rescue team [58, 80].

WSNs may incorporate a large number of sensor nodes. A sensor node can only

communicate with other sensor nodes within its limited transmission range. These sensors have the ability to communicate either among each other or directly to an external base station (BS). A BS may be a fixed or mobile node capable of connecting the sensor network to an existing communications infrastructure or to the Internet where a user can have access to the reported data [102]. Each sensor node bases its decisions on its mission, the information it currently has, and its knowledge of its computing, communication, and energy resources [4, 42]. Mainly, each sensor node contains sensing, processing, transmission, mobilizer, locating system, and power units, as needed [4].

The quick growth of wireless communication not only alleviates the dependency on wired traditional networks, but also increases the potential of mobile communication and boosts its computing power. In a WSN, each sensor node acts as a router with a sensing capability. Because sensor nodes can be mobile, the corresponding protocol should be able to handle rapid topology changes [93].

The decrease in the size and cost of sensors has increased the interest in the possible use of large set of disposable unattended sensors [50, 70]. This has ignited rigorous research in the past few years addressing the potential of collaboration among sensors in data gathering and processing and the coordination and management of the sensing activity and data flow to the sink. An example for such collaborative distributed sensors is a network with wireless links that can be formed among the sensors in an ad hoc manner [68].

As mentioned above, sensors are generally equipped with data processing and communication capabilities. The sensor sends the collected data, usually via radio transmitter,

to a command center (sink) either directly or through a data concentration center (a gateway) [1]. Since sensor networks are small and inexpensive, they can be produced and deployed in large numbers and their resources in terms of energy, memory, computational speed and bandwidth are severely constrained. Each device is equipped with a radio transceiver, a small microcontroller, and an energy source, usually a battery. The devices use each other to propagate data to a monitoring computer [41].

Aside from the very few setups that use mobile sensors [84], most of the network architectures assume that sensor nodes are stationary. On the other hand, supporting the mobility of sinks or cluster-heads (gateways) is sometimes considered essential [95]. Routing messages from or to moving nodes is more challenging since route stability becomes an important optimization factor, beside the energy, bandwidth, and other parameters. The sensed event can be either static or dynamic depending on the application [87]. For instance, an example of static events can be forest monitoring for early fire prevention, while in a target detection/tracking application, the event (phenomenon) is dynamic. Monitoring static events allows the network to operate in a reactive mode, which would create traffic when the event will be reported. Dynamic events in most applications need periodic reporting and consequently generate significant traffic to be routed to the sink [1].

In the past few years, intensive research that addresses the potential of collaboration among sensors in data gathering, processing, coordination and management of the sensing activity was conducted. In most applications, sensor nodes are constrained in energy supply and communication bandwidth. Therefore, innovative techniques to eliminate

energy inefficiencies that shorten the lifetime of the network and efficient use of the limited bandwidth are highly required [29,30]. Such constraints combined with a typical deployment of large number of sensor nodes pose many challenges to the design and management of WSNs and necessitate energy-awareness at all layers of the networking protocol stack. For instance, at the network layer, it is highly desirable to find methods for energy-efficient route discovery and relaying of data from the sensor nodes to the sink so that the lifetime of the network is maximized [4].

The following is a summary of WSNs' most important characteristics and features:

- WSNs have a highly dynamic nature, deeply embedded routers, resource constrained nodes, dense connectivity and unreliable asymmetric links [52,65,101].
- WSNs are feasible with very different network densities - from very sparse to very dense deployments - which requires adaptive protocols [46].
- Energy consumption is a major restriction in WSNs. Usually the battery of a sensor node is not rechargeable. Therefore, the need to extend the lifetime of a sensor node has a deep impact on the system and networking architecture [46,62,89].
- WSNs should be scalable [46].
- The architecture of WSNs is drastically different compared to traditional networks, in terms of a single node and the network as a whole, because of the principle differences in application scenarios and the underlying communication technology.

- Large-scale networks of wireless sensors have become an active subject in research [28]. For future sensor networks, the key parameters will be the success rate, energy consumption and time delay.

## 2.2 Routing in WSN

To facilitate the communication between two nodes without a direct communication link, routing protocols must be developed to support multi-hop communication [93]. An efficient routing mechanism can cause important power cost reductions and improve network longevity [94].

Devising a routing scheme for sensor-node-to-sensor-node communication is one of the challenging tasks in the deployment of sensor networks. Routing protocols in WSNs might differ depending on the application and network architecture [1, 4]. Many routing protocols have been specifically designed for WSNs where several factors such as energy efficiency, low latency, and success rate are necessary to take into account [1, 4, 46, 72].

Among the above factors, energy consumption is one of the most important concerns in a sensor network because each sensor node has to be in active mode during routing, communication and monitoring the environment [63, 64, 82]. Recent advances in WSNs have paved the way for many new protocols particularly designed for WSNs where energy awareness is of a paramount importance.

Routing is a relevant issue for maintaining good performance and successful operation in a network. It is elementary in all WSNs and is at the core of the whole network

control system. Routing is the process of delivering a message/packet across one or more networks via the most appropriate path. The main task of routing is to maintain data flow from the source to the destination, to maximize network performance. It refers to the distributed activity of building and using routing tables - one for each sensor node in the network - that helps incoming data packets to choose any efficient outgoing link to continue their travel towards the destination node [16, 45].

Routing in WSNs has different characteristics than that in traditional communication networks [40]. Address-based destination specification is replaced by a more general feature-based specification, such as, a geographic location [47, 95] or information gain [20].

A further concern is the topological deployment of nodes. This is application dependent and it influences the performance of the routing protocol. The deployment is either deterministic or self-organizing. In deterministic situations, the sensors are manually placed and data is routed through pre-determined paths. On the other hand, in self-organizing systems, the sensor nodes are distributed randomly creating an infrastructure in an ad hoc manner [36, 59, 79, 99].

Throughout the creation of an infrastructure, the process of setting up the routes is greatly influenced by energy considerations. Since the transmission power of a wireless radio is proportional to distance squared or even higher order in the presence of obstacles, multi-hop routing will consume less energy than direct communication. Usually sensors are distributed randomly over an area of interest and multi-hop routing becomes necessary [1, 61].

Routing in WSNs is very challenging because of several characteristics that differen-

tiate them from contemporary communication and wireless ad hoc networks.

- It is not feasible to build a global addressing scheme for the deployment of total number of sensor nodes. Therefore, classical IP-based protocols cannot be applied to WSNs. Another factor is used instead, such as the geographical location of the sensor nodes.
- Unlike typical communication networks, nearly all applications of WSNs require the flow of sensed data from several regions (sources) to a particular sink (destination).
- Generated data traffic contains momentous redundancy since several sensors may produce the same data within the vicinity of a phenomenon. To improve energy and bandwidth utilization, such redundancy needs to be exploited by the routing protocols.
- In terms of transmission power, on-board energy, processing capacity and storage, sensor nodes are tightly constrained. Therefore, sensor nodes need careful resource management [1].
- In communication networks the connection is symmetric, while in WSNs it is asymmetric, which makes applying communication network algorithms on WSNs more complex. For instance, an algorithm may have a good performance in communication networks but not in WSNs, or vice versa.
- In WSNs, there is a dense connectivity between sensor nodes, which is not the case for communication networks. This density adds to the complexity of routing algorithms.

As a result of such differences, many new algorithms have been proposed for the problem of routing data in sensor networks. In this part we survey recent routing protocols for sensor networks and present a classification for the various approaches pursued. As shown in Figure 2.1, routing algorithms are divided into two major classes: nonadaptive and adaptive. Nonadaptive or static algorithms do not adapt themselves to the changes in the network. However, adaptive algorithms change their routing decisions according to the changes in the network topology and traffic.

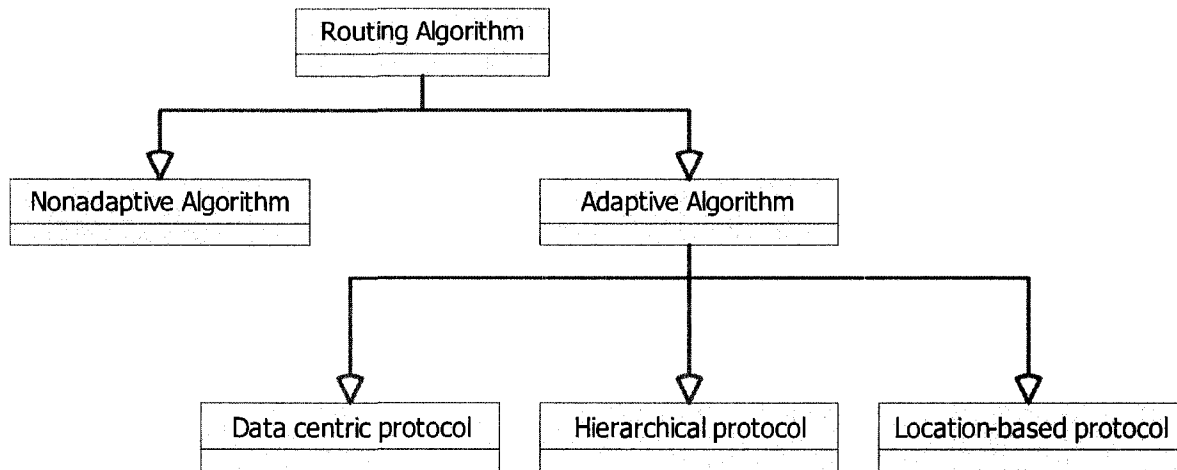


Figure 2.1: Routing Algorithms Hierarchy

### 2.2.1 Nonadaptive Routing

Non-adaptive routing algorithms do not base their routing decisions on measurements or estimates of the current traffic and topology. Instead, the choice of the route to use to get from one node to another is computed in advance, off-line, and downloaded to the routers when the network is booted. These routing algorithms do not base their routing

decisions on the current state of the network. This procedure is sometimes called static routing. A change, such as loss of a link or loss of a node is not compensated for, which means that any packet transmission will either have to wait for the failure to be repaired before restarting its trip, or will have to fail to reach its destination and quit the trip [86].

Some of the nonadaptive algorithms are described below:

### **Shortest Path Routing**

The shortest path routing technique is very common due to its simplicity and ease of use. This algorithm finds the shortest path between routers on the graph. It selects the shortest route between pair of routers. In the general case, the labels on the link could be computed as a function of the distance, communication cost, measured delay, bandwidth, average traffic, mean queue length, and other factors. For instance, in each node, to select the next node we choose the shortest distance, which means choosing the node that has the shortest path to the source node [86].

### **Flooding**

Another nonadaptive algorithm is flooding. Each node sends the packet to all the neighbor nodes. Flooding obviously generates huge numbers of duplicate packets. Flooding can be used in WSNs, with all messages transmitted by a station received by all other stations within its radio range [86].

Flooding has its own advantages and disadvantages: the probability of receiving the data at the destination is high, but the collision in the network and its energy

consumption is prohibitively high as well [100].

### 2.2.2 Adaptive Routing

Here we present some related works of adaptive routing protocols in WSNs. Modern networks generally use dynamic adaptive routing algorithms. The adaptive routing algorithms change their routing decisions with the changes in the network topology and network traffics. Adaptive algorithms differ in where they get their information, when they change the routers, and in the metric used for optimization [86].

Adaptive routing describes the ability of a system, through which routes are described by their destination, to modify the path the route takes through the system in response to a change in conditions. The adaptation is intended to allow as many routes as possible to remain valid and with reachable destinations, in response to the change. For example, when people are using a transport system, they can display adaptive routing. If a local railway station is closed, people can alight from a train at a different station and use another method, such as a bus, to reach their destination. Adaptive routing is normally used in data networking to describe the ability of a network to route around damage, such as loss of a node or a link between nodes, as long as other path choices are available. The adaptive routing protocols can be broadly classified into three main categories: data-centric, hierarchical and location-based [1]. Each routing protocol is illustrated under the proper category. In the following, the data-centric routing approach is detailed.

## **Data-centric protocols**

In lots of applications of sensor networks, it is impossible to assign global identifiers to each node due to the sheer number of nodes deployed. Such lack of global identification along with random deployment of sensor nodes makes it hard to select a precise set of sensor nodes to be queried. Therefore, data is usually transmitted from every sensor node within the deployment region with important redundancy. Since this is very inefficient in terms of energy consumption, routing protocols that are able to select a set of sensor nodes and utilize data aggregation during the relaying of data have been considered. This has led to data-centric routing, which is different from traditional address-based routing where routes are created between addressable nodes managed in the network layer of the communication stack [1, 51, 78].

Data-centric protocols are query-based and depend on the naming of desired data, which helps removing many unnecessary transmissions. 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 is necessary to specify the properties of data [1, 90].

Sensor protocols for information via negotiation (SPIN) [35] is a data-centric protocol, which considers data negotiation between nodes in order to eliminate redundant data and save energy. In SPIN the idea is to name the data using high-level descriptors or meta-data. Before transmission, metadata are exchanged among sensors by using a data advertisement mechanism that is the key feature of SPIN. Each node upon receiving new data, advertises it to its neighbors. The meta-data cooperation in SPIN solves the classic

troubles of flooding for example redundant information passing, overlapping of sensing areas and resource blindness, as a consequence, achieving a high energy efficiency. In SPIN there are three messages defined to exchange data between nodes. The first message is an ADV message to allow a sensor to advertise a particular meta-data. The second message is a REQ message to request the specific data, while the third message is a data message that carries the actual data [1].

### **Hierarchical protocols**

Like other communication networks, scalability is one of the main design challenges of sensor networks. A single-tier network can overload the gateway with the raise in sensors density. Such an overload might cause latency in communication and inadequate tracking of events. Also the single-gateway architecture is not scalable for a larger set of sensors covering a wider area of interest since the sensors are typically not capable of long-haul communication. Network clustering has been pursued in some routing approaches to let the system handle additional load and to be able to cover a large area of interest without degrading the service. The major aim of hierarchical routing is to efficiently maintain the energy consumption of sensor nodes by involving them in multi-hop communication in a particular cluster and by performing data aggregation and fusion in order to reduce the number of transmitted messages to the sink [1, 17].

Hierarchical protocols plan to cluster the nodes to save energy. Therefore, cluster heads can do some aggregation and reduction of data [1, 59]. The aim of these protocols is to control the energy consumption of sensor nodes in the face of varying network sizes.

Low-energy adaptive clustering hierarchy (LEACH) is one of the most popular hierarchical routing protocols for sensor networks. It is an energy-efficient communication protocol, which extends the system's lifetime and reduces the power consumption of WSNs [36]. The idea of LEACH is based on the received signal strength from clusters of the sensor nodes and use local cluster heads as routers to the sink. Since the transmissions are accomplished through these cluster heads rather than the sensor nodes, this technique leads to energy savings. In order to balance the energy dissipation of nodes, cluster heads change randomly over time. LEACH uses single-hop routing where each node can transmit directly to the cluster-head and to the sink. For this reason LEACH is not applicable to networks deployed in large regions [1,34,37]. The idea proposed in LEACH has been an inspiration for many hierarchical routing protocols [54, 55, 59, 60, 84, 99].

### **Location-Based protocols**

A large amount of the routing protocols in sensor networks require location information. Location-based protocols use the position information to spread the data to the desired regions rather than the entire network. Protocols that make use of the location information and topological deployment of sensor nodes are classified as location-based. In most cases, location information is required to calculate the distance between two particular nodes so that energy consumption can be estimated. There is no addressing scheme for sensor networks like IP-addresses. Therefore, location information can be used in routing data in an energy efficient way. For example, if the region to be sensed is known, using the location of sensors, the query can be spread only to that particular region that will

eliminate the number of transmission significantly [1].

Geographic adaptive fidelity (GAF) [94] is an energy-aware location-based routing algorithm designed mainly for mobile ad hoc networks, however may be applicable to sensor networks as well. GAF saves energy by turning off unnecessary nodes in the network without affecting the level of routing reliability. It forms a virtual grid of the covered area. Each node uses its GPS-indicated position to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Hence, this equivalence is exploited in keeping some nodes located in a particular grid area in sleeping state in order to save energy. Therefore, GAF can significantly enlarge the network lifetime as the number of nodes increases. A sample situation is depicted in Figure 2.2 [94]. In this figure, node 1 can reach nodes 2, 3 and 4, while nodes 2, 3, and 4 can reach node 5. Hence, two of nodes 2, 3 and 4 can be turned to sleep mode. Nodes change states from sleeping to active in turn to keep the load balanced. There are three states defined in GAF. These states are: ‘active’ reflecting participation in routing, ‘sleep’ when the radio is turned off, and ‘discovery’ for determining the neighbors in the grid [1]. Which node will sleep for how long is application-dependent and the related parameters are tuned for that reason during the routing process. To address the mobility issue, each node in the grid estimates its leaving time of the grid and sends it to its neighbors. The sleeping neighbors adjust their sleeping time for that reason and to maintain the routing fidelity. Before the leaving time of the active node ends, one of the sleeping nodes has to become active. GAF is implemented both for the mobility (GAF-mobility adaptation) and the

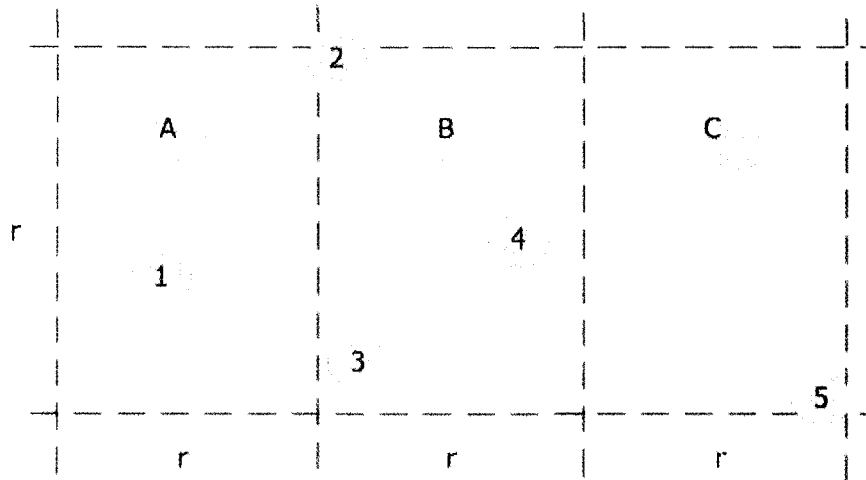


Figure 2.2: Example of virtual grid in GAF

non-mobility (GAF-basic) of nodes. GAF attempts to keep the network connected as in [84], by always keeping a representative node in active mode for each region on its virtual grid. Although GAF is a location-based protocol, it may also be considered as a hierarchical protocol, where the clusters are based on their geographic locations. For each particular grid area, a representative node acts as the leader to transmit the data to the other nodes [1].

## Chapter 3

# SWARM INTELLIGENCE AND ANT COLONY OPTIMIZATION

In this chapter we provide a brief overview of why and how biological inspired intelligent systems emerged. We briefly elaborate on how they can operate as a means of artificial intelligence inside a device or a system.

### 3.1 Swarm intelligence

There are many reasons why humans try to mimic and learn from biology. Throughout history, humans have always searched to imitate the mobility, appearance, functionality, intelligent operation, and thinking process of biological creatures. As humans, when we face hard technological problems, we like to turn to biology for inspiration. Insects for example excel at problem solving. They can solve their problems individually or

in groups, like in food gathering by ants for instance. A swarm of ants in the search for food demonstrates the notable capability of finding shortest paths between a found food source and the anthill [11]. In previous decades, researchers discovered a diversity of interesting insect and animal behaviors in nature. A group of ants forages for food. A flock of birds moves across the sky. A school of fish swim together. This kind of collective movement is called a swarm behavior [56]. Information acquired from studying biological systems can apply to engineering problems through the use of sophisticated methods for large databases and tools for modeling and simulating complex systems. By using ants and other social swarms as models, we can create software agents that can solve complex problems, such as rerouting of traffic in a busy telecommunication network for example [9].

Researchers in the field of artificial life have studied how to model biological swarms to understand how such social insects interact, reach goals, and evolve. This study led to the development of important theories on how ants communicate as a group, which made engineers more interested in adapting swarm intelligence. The swarm of ants is attractive from the perspective of computer science, because of the possibility to simulate and potentially exploit this behavior to solve algorithmic problems. In a colony, each insect has its own plan; and the entire group seems to be highly organized, and individual activities do not require any supervision. Also, they cooperate at the colony level that is largely self-organized. Although the interactions such as one ant following the trail left by another are simple, together they can solve difficult problems like finding the shortest route among many possible paths to a food source.

Swarm intelligence is this cooperative behavior of a group of social insects [48,76,92]. It is based on the study of collective behavior in decentralized, self-organized systems. The term 'swarm intelligence' was introduced by Beni and Wang in 1989, in the context of cellular robotic systems [25]. Although there is normally no centralized control structure describing how individual agents behave, local interactions between such agents are global.

In Figure 3.1, for instance, the ants have to decide which way to go. A number of insects leave the nest at the same time. Each ant takes a different path while marking it with pheromones. Pheromones are attractive chemical substances which catches the attention of other ants. They are used for indirect communication between ants, a phenomenon known as stigmergy [49,67]. Pheromone trails allow the ants to forage efficiently. Artificial ants continuously explore different paths and pheromone trails to provide backup plans. Thus, if one link fails, a pool of alternatives would already be left [38,74].

In this figure the ant that chooses the shorter path returns to the nest faster. Because the shorter path has a higher concentration of pheromone, it will attract more ants than the longer routes. Although any single ant could be said to have the ability of finding a short path from the anthill to a nearby food source, the probability of this happening is very small. However, when many ants collaborate on finding food, using pheromone trails as a simple indirect form of communication, the swarm of ants seems to be able to find a shortest path successfully. Another key characteristic is their capability to adapt to a varying environment. If an obstacle is placed on the path from the food source

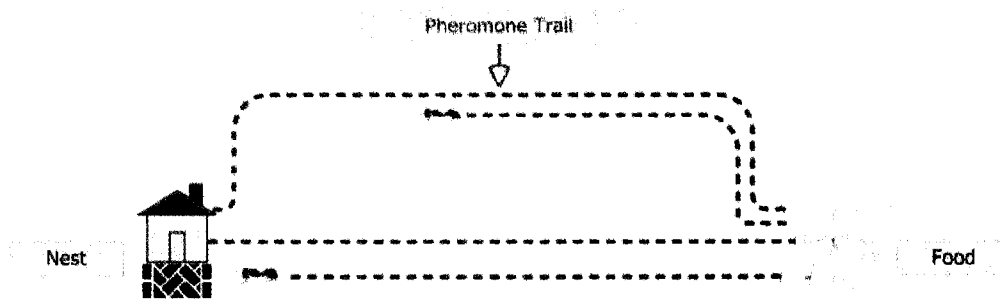


Figure 3.1: Pheromone Trails

back to the anthill, ants are capable of finding the shortest path around the obstacle, and possibly find food sources closer to the anthill. Ant-inspired algorithms have the capability of finding short paths in graphs, and show an inherent adaptability that could be utilized to solve dynamic problems such as routing in a network [77].

Ants use reinforcement learning to discover the best way. In reinforcement learning, the intelligent system is just given a goal to reach. The system then achieves its goal by a trial and error interaction with the environment. For the interactions that take the system close to the target, a positive reward is received while going away from the target, a negative reward is assigned [85]. Some researchers have addressed the reinforcement learning of an artificial system by introducing a concept called pheromone decay. When the chemical evaporates rapidly, longer paths will have trouble maintaining stable pheromone trails. This has been used for telecommunication networks [9, 81].

The social behavior of ants has a number of attractive characteristics, including adaptation, robustness and distributed, decentralized nature, which are well collected for routing in modern communication networks [49, 97].

Swarm intelligence is divided to two main categories: Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) [8]. ACO is an optimization algorithm that can be used to find approximate solutions to difficult combinatorial optimization problems. In ACO virtual artificial ants find solutions by moving on the problem graph and imitating real ants. ACO has been successfully applied to a remarkable number of optimization problems [8, 15, 25, 43].

NASA has explored the use of swarm technology for planetary mapping. The U.S. military has studied swarm techniques for controlling unmanned vehicles. Swarm technology is particularly attractive because it is inexpensive, robust, and simple. An agent is an entity that acts and recognizes. A main goal in the field of artificial intelligence, is the study and creation of rational agents like robots which are programmed to do certain tasks [12, 73].

In the well-known Traveling Salesman Problem (TSP), a person must find the shortest route to visit a given number of cities, each exactly once [21]. The classic problem is difficult. With just fifteen cities (Figure 3.2) there are billions of route possibilities [9]. Researchers exploited the use of ant-like agents to find a solution. The approach relies on artificial ants that lay and follow the equivalent of pheromone trails. The amount of the chemical is inversely proportional to the overall length of the tour. The longer the distance, the less pheromone each of the links receives. Therefore, after all the ants fulfill their tours and spread their pheromone, shorter links will be richer with the chemical than the longer ones. The artificial ants are then released to travel over the cities again, however this time they are guided by the earlier pheromone trails (high-concentration

links) as well as by the inter-city distances (nearby locations). In general, the two criteria pheromone strength and inter-city distance are weighted roughly equally [9]. Scientists

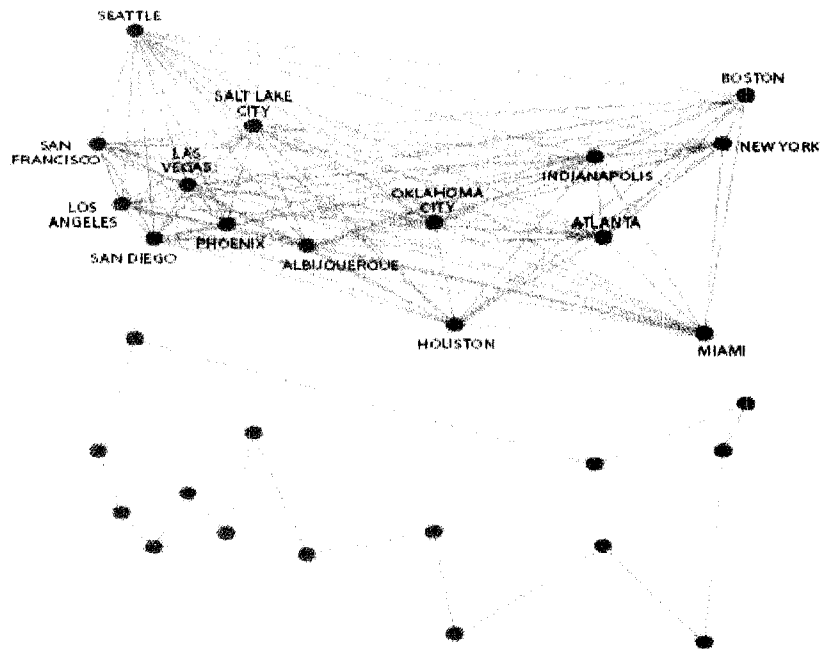


Figure 3.2: Traveling Sales Ants

have shown that they can obtain near-optimal routes by using artificial ants [16]. Another example, artificial ants give the best solution to the classic quadratic assignment problem, in which the manufacture of a number of goods must be assigned to different factories as to minimize the total distance over which the items need to be transported between facilities. In a related application, David Gregg of Unilever in England and Vincent Darley of Bios Group in Santa Fe, N.M., reported that they had developed an ant-

based method for decreasing the time it takes to perform certain tasks in a Unilever plant, where the system must efficiently schedule different storage tanks, packing lines, chemical mixers, and other tools [9].

Network traffic can be rerouted on the fly with software agents that imitate ants. In Figure 3.3, a transmission that needs to go from node A to node B must use a number of intermediate nodes. If a part of the shortest path between the two locations is inaccessible, the system must redirect the transmission through an alternative path. Software agents can perform this rerouting automatically in a way that is similar to how ants raid different food sources. An inaccessible path is like an empty food source [9].

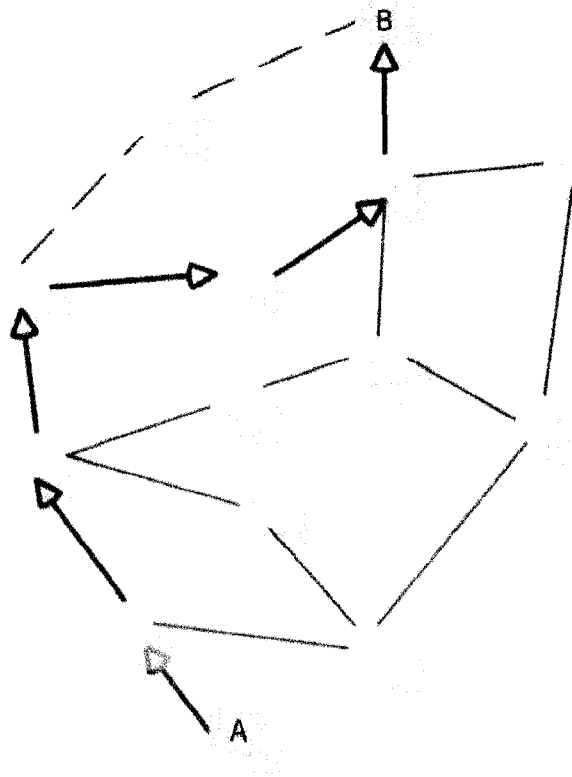


Figure 3.3: Network Traffic

To handle conditions such as a bad weather in an airport or phone lines being overloaded, scientists have invented a routing technique in which ant-like agents deposit bits of information or virtual pheromones at the network nodes to reinforce paths through accessible regions. Also, an evaporation mechanism adjusts the node information to disfavor paths that go through busy areas. Like that, busy routes experience more evaporation than the reinforced ones and vice versa. Several companies are exploring this approach for handling the network traffic like France Telecom, British Telecommunications, and U.S. MCI Worldcom. The latter has been investigating the use of artificial ants to manage the company's telephone network as well as customer billing [9]. In fact, extensive tests showed that ant-base methods can outperform OSPF, the protocol that the Internet uses, where traffic is unpredictable.

A number of ACO-based routing algorithms are described below.

## **3.2 AntNet Routing Algorithm**

AntNet is an adaptive network routing algorithm based on ACO, which is first proposed by Di Caro and Dorigo [16]. It is a distributed, mobile agent-based Monte Carlo system, inspired by the foraging behavior of ant colonies for solving optimization problems [14]. In AntNet a group of mobile agents (or artificial ants) make trails between pairs of nodes, discovering the network concurrently and exchanging obtained information to update the routing tables [7, 15]. The communication between the agents is indirect and asynchronous, mediated by the network itself. AntNet's agents concurrently explore

the network, exchanging collected information [6]. These agents are divided into two classes, the forward ants and the backward ants [5]. The communication among the agents is indirect and asynchronous, mediated by the network itself. AntNet was shown to outperform other routing algorithms e.g. OSPF, SPF, BF, Q-R, PQ-R and Daemon [16].

### **3.3 Basic Ant Routing Algorithm**

The Basic Ant Routing (Basic) algorithm is inspired from the AntNet algorithm [103]. In this algorithm, a forward ant is launched from the source node toward the destination node at given time intervals. According to the link probability distribution, each forward ant searches for the destination by selecting the next hop node. At first, all the links have equal probability. While moving forward, each forward ant remembers the list of nodes it has visited and tries to avoid going over the same node.

### **3.4 Sensor-driven Cost-aware Ant Routing Algorithm**

One of the problems of the basic ant-routing algorithm is that the forward ants normally take a long time to find the destination, even when a forward list is used. This is because ants initially have no idea on the location of the destination. Just after one ant finds the destination and travels back along the links, their link probabilities are uploaded. In Sensor-driven Cost-aware Ant Routing (SC) algorithm, it is supposed that ants have sensors [103]. Therefore, they can smell food right at the start. That is not an unrealistic assumption for sensor networks, since feature-based routing dominates

address-based routing in that space. A number of characteristics, such as geographic location, have a natural potential field. If the destination does not have a clear hint, pre-building the feature potential is sometimes still possible. Cost awareness generalizes the objective of the shortest path length. Thus, ants can apply other routing metrics as well, such as energy-aware routing [103].

### **3.5 Flooded Forward Ant Routing Algorithm**

Even by adding sensors, forward ants can be misguided due to moving destinations or barriers. Flooded Forward Ant Routing (FF) algorithm makes use of the broadcast channel in WSNs. When a forward ant begins at the source, it informs all its neighbors to look for the food, which is then passed on between neighbors, until the destination is found. Then ants go backward to the source leaving pheromone trails on those links. Only ants that are closer to the food will join the food searching process to control the flooding [103].

### **3.6 Flooded Piggybacked Ant Routing Algorithm**

Due to the asymmetric and dynamic properties of sensor networks, single path routing is likely to have high loss rates. Hence, multi-path routing like flooding is very robust and has a high success rate. In Flooded Piggybacked Ant Routing (FP) algorithm, forward ants and data ants are joined by using constrained flooding in the FF algorithm to route the data, while still searching good paths [103].

# Chapter 4

## PROPOSED ALGORITHMS

In this chapter, we propose four adaptive routing algorithms based on swarm intelligence: the Adaptive Routing (AR) algorithm, the Improved Adaptive Routing (IAR) algorithm, the Multimedia-enabled Improved Adaptive Routing (M-IAR) algorithm and the Many-to-One Improved Adaptive Routing (MO-IAR) algorithm. We use the notion of location based convergence with the ant-based intelligence so that next-hop selection process converges toward the destination as fast as possible. All the sensor nodes take routing decisions based on neighborhood information only. Therefore, there is no need to maintain the global state of the sensor nodes.

In the following section we describe the AR and IAR algorithms. Both algorithms are designed to optimize several criteria such as energy consumption, latency and success-rate.

In section 4.2 and section 4.3 we introduce M-IAR and MO-IAR algorithms. We explain the implementation and performance analysis of the proposed algorithms in Chapter

5.

## 4.1 AR and IAR: Adaptive Routing and Improved Adaptive Routing for WSNs

The proposed Adaptive Routing (AR) algorithm is based on the Adaptive ant-based Dynamic Routing (ADR) algorithm, originally intended for packet-switched communication networks [57]. We modified the ADR algorithm by removing the queue parameters. However, we maintained the reinforcement learning concept of ADR.

The proposed AR uses probability distribution at each sensor node in the network, where a routing table is maintained (see Figure 4.1). Each routing table contains  $|N_k| * N$  entries where  $|N_k|$  correspond to the set of neighbors of node  $k$ , while  $N$  is the number of sensor nodes in the network. Ants use this routing table to choose the next favorable neighbor node [32]. In Figure 4.1 each row in the table corresponds to a neighbor and

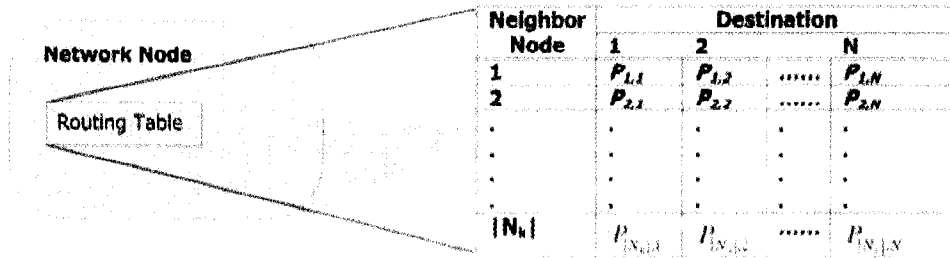


Figure 4.1: Routing table structure for node  $k$

each column refers to a destination. We define the probability  $P_{i,j}$  of a node  $k$  as the probability of desirability of choosing the node  $i$  as the neighbor of  $k$  to go to the des-

mination node  $j$ . Based on this probability distribution, ants explore new and possibly better routes. Once new routes are found, the next-hop probabilities are updated in the routing table, so that the next set of ants can follow this route. The following probability constraint must be satisfied by all routing table entries [16, 32]:

$$\sum P_{i,d} = 1, i \in neighbors(k), d \in [1, N] \quad (4.1)$$

We initialize all the routing tables with equal probabilities. In the proposed algorithms, we employ two types of ants [16]: (i) forward ant ( $F_{\text{ant}}$ ), which travels from the source node ( $s$ ) to the destination node ( $d$ ). Each  $F_{\text{ant}}$  searches for the destination by selecting the next hop node according to the link probability destination. (ii) backward ant ( $B_{\text{ant}}$ ) is generated by  $F_{\text{ant}}$ , when  $F_{\text{ant}}$  reaches the destination  $d$ . The  $B_{\text{ant}}$  will then come back to  $s$  by using the information already supplied by  $F_{\text{ant}}$ . However, the  $B_{\text{ant}}$  uses a reinforcement learning algorithm [18, 44] in order to get a better and more efficient route than the one chosen by the  $F_{\text{ant}}$  and at the end it updates the routing tables of the reverse-visited sensor nodes. During the backward travel, the cost from the destination to each node in the path is recorded; rewards are then given according to the relative goodness of the path. Probability of the nodes in the path is updated according to the rewards [32].

From each sensor node  $k$  having  $|N_k|$  neighbors,  $F_{\text{ant}}$  selects the next hop node  $i$  with a probability of  $P'_{i,d}$ .  $P'_{i,d}$  is the normalized sum of the probabilistic entry  $P_{i,d}$  of the routing table with a correction factor  $C_{k,i}$  and the weight factor  $\beta$ , which is computed as

follows:

$$P'_{i,d} = \frac{P_{i,d} + \beta \times C_{k,i}}{1 + \beta \times (|N| - 1)} \quad (4.2)$$

where,  $C_{k,i}$  is the cost from the current node  $k$  to the neighbor node  $i$ .  $C_{k,i}$  is calculated as follows:

$$C_{k,i} = 1 - \frac{D_{k,i}}{\sum_{j=1}^{|N_k|} D_{k,j}} \quad (4.3)$$

where  $D_{k,i}$  is the distance between current node  $k$  and its neighbor node  $i$ .

As shown in Equation 4.3, the heuristic correction  $C_{k,i}$  is proportional to the distance  $D_{k,i}$ . The value of  $\beta$  in Equation 4.2 weights the desirability of the correction factor  $C_{k,i}$  with respect to the probability values  $P_{i,d}$  stored in the routing table. The coefficient  $\beta$  has a value between zero and one. Through experiment the optimal value of  $\beta$  is 0.1. The simulation results presented in Chapter 5 for the proposed AR algorithm showed not very satisfactory results with regards to the requirements of WSNs. For example, we have observed for the simulation result that to receive 40 packets, the  $F_{\text{ant}}$  has to visit around 400 nodes, which is assumed to be non energy-efficient. Therefore, we further modified the AR algorithm, which results the Improved Adaptive Routing (IAR) algorithm.

In the IAR algorithm, we propose a modified heuristic correction factor  $A_{i,d}$  that is the cost from the neighbor node  $i$  to the destination node  $d$  to find the following probability  $P'_{i,d}$  [32]:

$$P'_{i,d} = A_{i,d} \times \frac{P_{i,d} + \beta \times C_{k,i}}{1 + \beta \times (|N| - 1)} \quad (4.4)$$

where the coefficient  $A_{i,d}$  is given by:

$$A_{i,d} = \frac{1}{\lambda \times D_{i,d}} \quad (4.5)$$

In the above equation  $D_{i,d}$  is the distance from the neighbor node  $i$  to the destination node  $d$  and  $\lambda$  is an optimization factor for  $A_{i,d}$ , which has a value between zero and one. Through experiment the optimal value of  $\lambda$  is 0.7. For example, for geographic routing, we may estimate the node's cost by [32]:

$$\sqrt{(x_d - x_i)^2 + (y_d - y_i)^2} \quad (4.6)$$

where  $(x_i, y_i)$  is the location of the current node and  $(x_d, y_d)$  is the location of the destination. When a  $F_{\text{ant}}$  moves toward its destination  $d$ , it remembers the list of nodes it has visited while updating a two dimensional matrix. Subsequent forward ants use this list to avoid visiting the same node. If a node is already visited, another unvisited neighbor node will be selected. Also, if the visited nodes by a  $F_{\text{ant}}$  are larger than half of the total number of nodes, the  $F_{\text{ant}}$  dies, which indicates that the path it was following was not efficient. The  $B_{\text{ant}}$  works similarly except that during the backward travel, every intermediate node is treated like a destination and its associated probabilities are changed. The function 'change of probability' is a negative exponential, with the exponent proportional to the cost between the current node  $k$  and the destination node  $d$  through the neighbor node  $i$  [32]:

$$\Delta P = e^{-\gamma * d_{i,d}^k} \quad (4.7)$$

where  $\gamma$  is a coefficient factor to control the change of probability for  $B_{\text{ant}}$ . It has a value between zero and one. Through experiment the optimal value of  $\gamma$  is 0.5.  $d_{i,d}^k$  is the distance between the current node  $k$  and the neighbor node  $i$  plus the cost between the neighbor node  $i$  and the destination node  $d$  and can be expressed as  $D_{k,i} + D_{i,d}$ . When

a  $B_{\text{ant}}$  arrives at node  $i$ , the entry in the routing table corresponding to the node  $i$  from which the ant has just come increases by  $\Delta P$  as following [16, 57] [32]:

$$P_{i,d} = \frac{P_{i,d} + \Delta P}{1 + \Delta P} \quad (4.8)$$

Similar to [16] and [57], the other entries in the routing table of that node are decreased as following [32]:

$$P'_{i',d} = \frac{P_{i',d}}{1 + \Delta P}, i' \in \text{neighbors}(k), i' \neq i \quad (4.9)$$

Algorithm 1 and algorithm 2 show the pseudo-code of the proposed IAR algorithm for the  $F_{\text{ant}}$  and the  $B_{\text{ant}}$  respectively.

---

**Algorithm 1:** The Proposed IAR Algorithm for Forward-Ant

---

Forward-Ant(source-node, current-node, destination-node)

**begin**

**if** *destination is reached* **then**

        └ Create a new Backward-ant and Copy forward-list to backward-list

**else**

        └ Add current-node to forward-list

**if** *Less than half of the sensor nodes visited* **then**

        └ Choose the next neighbor according to the following probability

$$P'_{i,d} = A_{i,d} \times \frac{P_{i,d} + \beta \times C_{k,i}}{1 + \beta \times (|N| - 1)}$$

**if** *selected neighbor visited* **then**

            └ choose another neighbor node

**else**

        └ Perish Forward-Ant

**end**

---

---

**Algorithm 2:** The Proposed IAR Algorithm for Backward-Ant

---

Backward-Ant(source-node, current-node, destination-node)

**begin****if** *source is reached* **then**

└ Perish Backward-Ant

**else****for** *all neighbor nodes* **do****if** *selected neighbor node visited by Forward-Ant* **then**└  $P_{i,d} = \frac{P_{i,d} + \Delta P}{1 + \Delta P}$ **else**└  $P_{i,d} = \frac{P_{i,d}}{1 + \Delta P}$ 

└ Remove first item of Backward-list

└ Move Backward-Ant to selected neighbor node

**end**

---

## 4.2 M-IAR: Multimedia Sensory Data Routing for WSNs

Recently, there are noteworthy number of applications that incorporate wireless multimedia sensors such as audio, video and images. In this section, we propose Multimedia-enabled Improved Adaptive Routing (M-IAR) that is optimized for single-source-to-single-destination multimedia sensory data traffic. It is an extension of the proposed IAR algorithm.

First-generation sensor nodes used to be very simple and mostly consisted of static

sensory data. However, with the emergence of complex second-generation multimedia sensors capable of delivering multi-modal sensory information, existing routing protocols seem to show poor performance [104]. Multimedia sensory data poses several unique challenges on the routing protocols of these systems such as real-time delivery, tolerable end-to-end delay, proper bandwidth, jitter, and frame loss rate. Although many routing protocols have addressed routing over Internet and Mobile Adhoc Network (MANet) [66, 83, 91, 104], only very few attempts have addressed the problem of multimedia data routing over resource constrained WSNs. The multi-hop nature of most WSN applications is the main source of these challenges. The example of multimedia traffic over a WSN might be forwarding images, video, and audio data to a sink node. Here we extend IAR by incorporating two extra multimedia QoS parameters, namely the end-to-end delay and jitter. M-IAR finds the shortest path rapidly by visiting least number of nodes.

In M-IAR, we modify the notion of delay factor assumed in IAR. IAR assumed that the inter-hop communication delay is negligible compared to the local packet processing delay within a node and this local processing delay is equal throughout the WSN. Thus, delay was assumed to be proportional to the number of visited nodes. This is a flawed assumption for multimedia traffic, because multimedia traffic is sensitive to both local processing delay as well as the transmission delay. In M-IAR we assume that both the number of nodes and the distance between any two of them have impact on the resulting end-to-end delay and jitter. Thus, finding the shortest path with the least number of forwarding nodes will help us in achieving the least end-to-end delay and better jitter

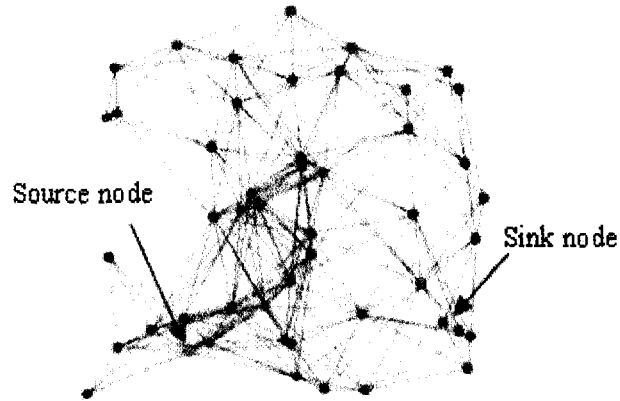


Figure 4.2: M-IAR routing in WSN

condition. Figure 4.2 shows the WSN spatial model that we use to evaluate the routing algorithm. We assume that the sensor nodes have a limited range and each sensor node is thus within the proximity of a limited number of neighbors.

Algorithm 3 and algorithm 4 shows the pseudo-code of the proposed M-IAR algorithm for the  $F_{\text{ant}}$  and the  $B_{\text{ant}}$  respectively.

---

**Algorithm 3:** The Proposed M-IAR Algorithm for Forward-Ant

---

Forward-Ant(source-node, current-node, destination-node)

**begin**Define equal initial probability  $P_{i,d}$  for each sensor node;**if** *Less than half of the sensor nodes visited* **then**

Choose the next neighbor according to the following probability;

$$P'_{i,d} = A_{i,d} \times \frac{P_{i,d} + \beta \times C_{k,i}}{1 + \beta \times (|N| - 1)}$$

Update the routing table;

Calculate the delay;

**if** *selected neighbor visited* **then**

└ Choose another neighbor node;

**else**

└ Add current-node to forward-list;

**if** *destination is reached* **then**

└ Calculate the end-to-end delay;

└ Calculate jitter;

└ Create a new Backward-ant;

└ Copy forward-list, delay and jitter parameters to backward-list;

**else**

└ Perish Forward-Ant;

**end**

---

---

**Algorithm 4:** The Proposed M-IAR Algorithm for Backward-Ant

---

Backward-Ant(source-node, current-node, destination-node)

**begin****if** *source is reached* **then**

└ Perish Backward-Ant;

**else****for** *all neighbor nodes* **do****if** *selected neighbor node visited by Forward-Ant* **then**└  $P_{i,d} = \frac{P_{i,d} + \Delta P}{1 + \Delta P}$ **else**└  $P_{i,d} = \frac{P_{i,d}}{1 + \Delta P}$ 

Remove first item of Backward-list;

└ Update the delay parameter;

└ Move Backward-Ant to selected neighbor node;

**end**

---

$B_{\text{ant}}$  does not need any local broadcast to find the probability because it simply uses the parameters containing the probability and other contextual information supplied by its parent  $F_{\text{ant}}$ . This allows the  $B_{\text{ant}}$  to save resources such as bandwidth and energy and, helps in reaching the source node faster. M-IAR can be configured for both acknowledgment-based and non acknowledgment-based routing. To imitate the acknowledgment-based traffic, we do not transmit a new  $F_{\text{ant}}$  unless the resulting  $B_{\text{ant}}$  reinforces the path chosen by the  $F_{\text{ant}}$  and reports it to the sender. This will make sure that the packet is successfully received by the sink node. On the other hand, M-IAR waits for the acknowledgment message from the  $B_{\text{ant}}$  for a certain period of time. Af-

ter timeout, the source node sends a new  $F_{\text{ant}}$  assuming the earlier packet is lost. This feature is suitable for some real-time multimedia application that tolerates some packet losses [71].

### 4.3 MO-IAR: Many-to-One Sensory Data Routing in WSNs

Many WSN applications such as earthquake assessment and remote object tracking require that the captured event by  $n$  number of sensor nodes be transmitted to the base station within tolerable packet loss. Some literature calls this a many-to-one type of communication [24].

The proposed protocol operates in two phases. **Phase1:** The algorithm assumes that each sensor node knows its location and the location of the destination a priori. This can be achieved using GPS technology for example. Once the sensor nodes are initially deployed, each sensor node locally broadcasts a HELLO message to its neighbors to form the neighborhood table. We are assuming that the neighborhood table is the same as the routing table. Once a sensor node hears any HELLO message from any of its neighbor, it records the ID, location of the neighboring node and distance between them. After a predefined time, depending on the density of the WSN, the protocol assumes that all the sensor nodes have identified their local neighbors. We assume that the sensor network has a static destination node and  $N$  number of sensor nodes among which each sensor node sends  $n$  number of forward ants successively to find the shortest path between

itself and the sink. Each  $F_{\text{ant}}$  uses the same ant-routing algorithm detailed in Algorithm 1 to find the best next-hop neighbor node. Before leaving the current node, the  $F_{\text{ant}}$  updates the probability value of the chosen next-hop neighbor in the routing table. Each  $F_{\text{ant}}$  also carries some parameters in its packet header such as details of visited nodes, corresponding probability values, total number of hops visited, distance between each link, and neighbors of the visited nodes. The same process goes on until the destination is reached. After reaching the destination, the  $F_{\text{ant}}$  creates a  $B_{\text{ant}}$ , destroys itself, and hands over the aggregated routing information to the  $B_{\text{ant}}$ .

The  $B_{\text{ant}}$  follows the same trail followed by its parent  $F_{\text{ant}}$ , and reinforces the path by changing the probability values. A  $F_{\text{ant}}$  updates the probability value of the next-hop neighbor in the routing table of the current node. While, the  $B_{\text{ant}}$  first increases the probability value of the current node in its routing table if it was visited earlier by the parent  $F_{\text{ant}}$  and decreases the probability value of the non-visited neighbor nodes of the current node. Each  $B_{\text{ant}}$  uses the same ant-routing algorithm detailed in Algorithm 2. Upon reaching the source node back, the  $B_{\text{ant}}$  destroys itself. The similar shortest path exploration process goes on for the next  $(n-1)$  number of forward and backward ants. The shortest path between each source node and the given destination is calculated once the  $n^{\text{th}}$  backward ant reaches the source. A similar process takes place in the first phase for each of the  $(N-1)$  number of sensor nodes.

**Phase2:** As soon as the shortest path between each of the  $(N - 1)$  sensor nodes and the destination is known, the algorithm initiates phase 2. This phase employs the data ants to route the actual data captured by  $|N_S|$  number of source nodes toward the

destination node. We define two extreme scenarios for this phase. One of the scenarios might arise if the sensory data generated by the captured events do not follow any common shortest path. In this case, there will be no congestion at all and the results should be similar to the one proposed in [32]. This special case is illustrated in Figure 4.3, which shows the shortest paths between the source nodes 1, 4, 8, 9, 10, 26, and 34 to the destination node 18. The figure also shows that all the shortest paths have disjoint sensor nodes and thus, each source node can send its captured packets in parallel. In this scenario, the source nodes do not need to implement any congestion avoidance algorithms. The second scenario arises when two or more source nodes have at least one

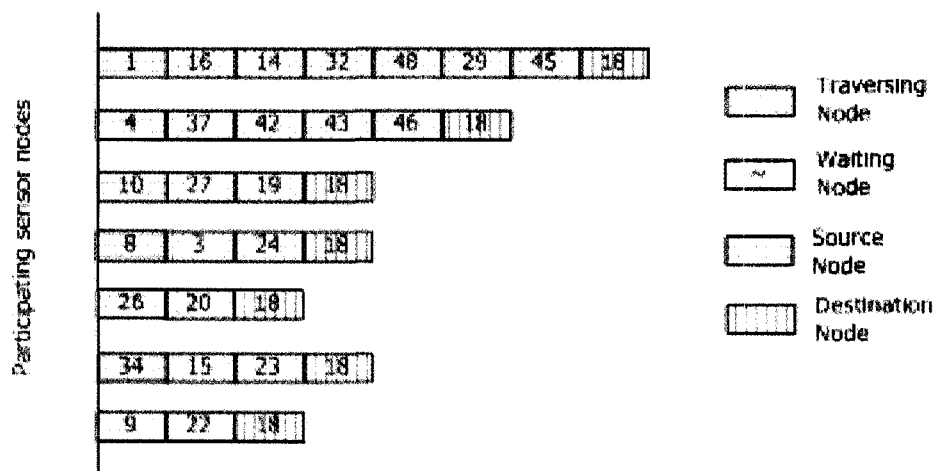


Figure 4.3: A many-to-one routing scenario with no common next-hop neighbor node

common neighbor in their shortest path. This scenario might be the result of periodic data captured by several sensor nodes or a number of events that simultaneously trigger several sensor nodes within the WSN. In this case, the algorithm implements a lightweight congestion control mechanism to avoid collision. The advantage of this approach is that

by mapping the shortest path with the neighborhood information, a data ant can easily guess the collision probability. Figure 4.4 illustrates how a data ant guesses the number of probable source nodes that might be contending to access the channel for sending their captured sensory data. We assume that at any particular instant, every sensor node falls

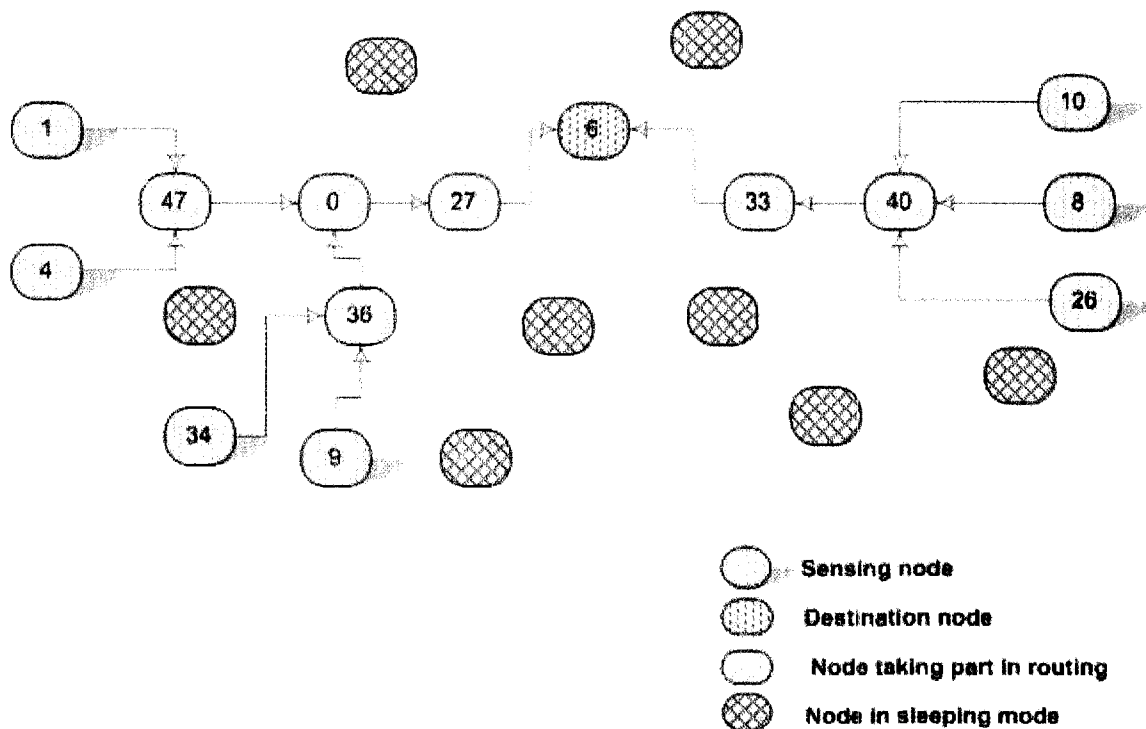


Figure 4.4: A many-to-one routing scenario where several sensors send data to the sink

under one of the three categories: either it is busy in sensing an event, or work as a routing node i.e. takes part in relaying the sensed data, or is in sleeping mode.

Looking at the shortest path provided by phase 1 and mapping it with the routing table, a data ant guesses the neighbors that might be under collision. As shown in Figure 4.5, seven source nodes including node 1, 4, 8, 9, 10, 26 and 34 have sensing data that

needs to be sent to destination node 6. Because node 1 and 4 have a common neighbor, which is 47, node 9 and 34 have a common neighbor 36, and node 8, 10 and 26 have a common neighbor 40, they need to run the congestion control algorithm to avoid any packet loss. Algorithm 5 serves as the congestion control mechanism implemented by each data ant experiencing congestion.

---

**Algorithm 5: MO-IAR Algorithm for Data-Ant**

---

Data-Ant(source-node, current-node, destination-node, shortest-path, packet)

**begin**

**if** *destination is reached* **then**

        └ Perish Data-Ant

**else**

**if** *current-node == source-node* **then**

            Find the neighboring nodes' shortest paths from the routing table

            Determine probability of collision based on common next-hop neighbor

            Run binary exponential backoff algorithm to calculate sending delay

        └ Send packet to the next-hop neighbor

**else**

            Enqueue route-thru packets in the buffer

            Dequeue to transmit packet to the next-hop neighbor in the shortest

        └ path

**end**

---

As shown in Algorithm 5, the data ant has two salient states; the initial state when it remains within the source node and the routing state where it travels the route-

thru nodes. In the first state, the congestion control algorithm implements the binary exponential backoff algorithm to regulate the channel access by each contending data ant and in the routing state the congestion control algorithm maintains the buffer to the route-thru traffic [31].

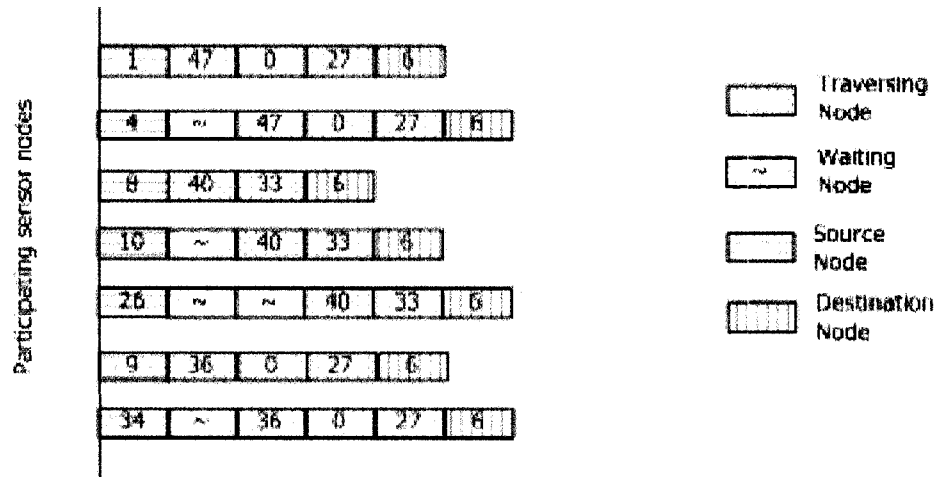


Figure 4.5: A many-to-one routing scenario with common next-hop neighbor node

We use Figure 4.5 to explain the different states mentioned in algorithm 5. When the data ant is in the source node, it waits to access the channel to forward the captured sensory data to the next-hop neighbor. Each contending source node runs an exponential backoff algorithm to determine the delay offset. The protocol schedules the channel access in the following manner. The node having the lowest node index will send its packet first without any delay. The subsequent nodes use the binary exponential backoff algorithm to calculate their channel access time. Each intermediate routing node maintains a queue similar to the one shown in Figure 4.6 where the algorithm implements a queue-based packet scheduling algorithm to service the route-thru packets [31]. Due to the

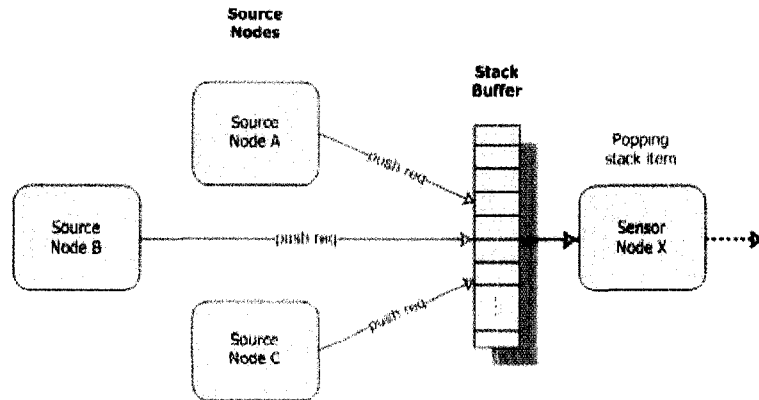


Figure 4.6: Buffer management scheme for servicing route-thru packets

convergence nature of the many-to-one routing paradigm, the shortest paths might merge or cross over at any intermediate node. Thus, the congestion control algorithm pushes the incoming route-thru packets to the queue and provides service according to the First Come First Serve (FCFS) principle. Regarding the destination node, we assume that it is not limited in buffer or bandwidth to handle incoming traffic from its neighboring nodes.

## Chapter 5

# IMPLEMENTATION AND PERFORMANCE ANALYSIS

We have designed a java-based simulator in order to test the performance of all of the proposed routing algorithms. Figure 5.1 shows the simulation interface we have developed for evaluating the proposed algorithms. The simulator helps initializing the number of sensor nodes to be deployed, their spatial location and their connectivity. It also allows selecting the source nodes, the destination node, types of algorithm to compare with, and their parameters. It has two modes of operation: the nodes can be randomly generated or uniformly distributed. For simulations, we used networks with randomly distributed nodes as it is more realistic. Based on the connectivity and spatial layout of the sensor nodes, the traffic and the degree of congestion might vary. Before presenting the simulation results, we first want to introduce some of the simulation parameters. We chose the total number of sensor nodes  $N$  as 49, total number of source nodes  $N_S$  as 7

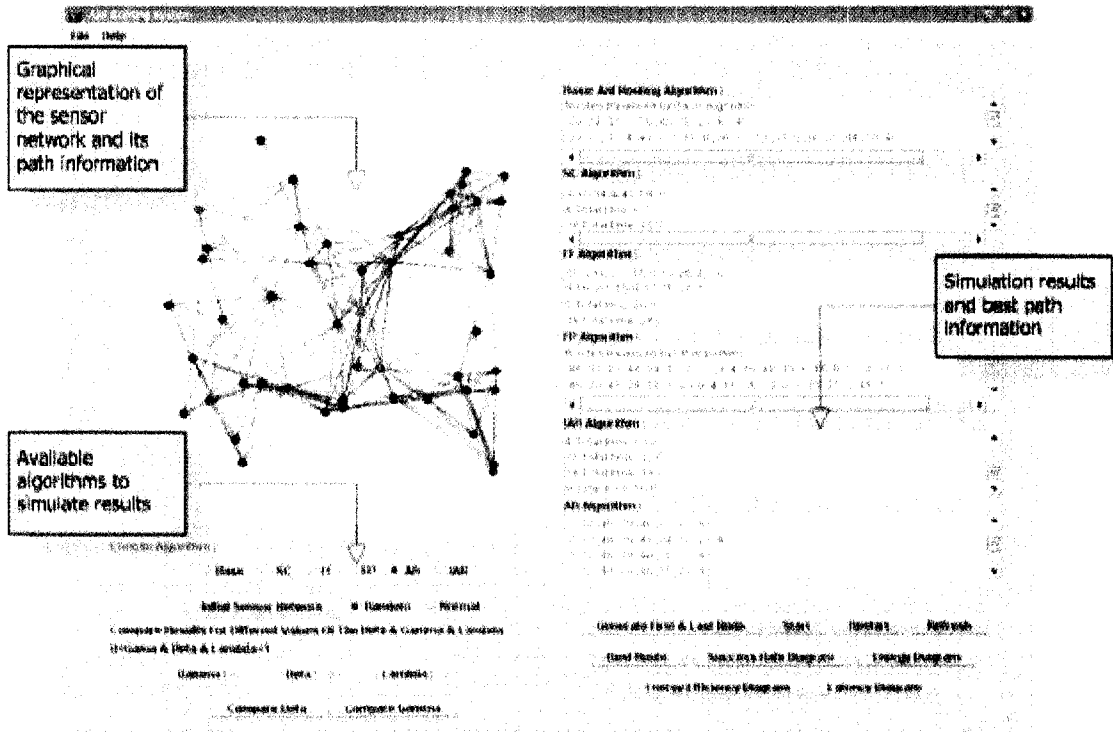


Figure 5.1: The simulator GUI

and the range of wireless transmission of each node as 10 meters. As a wireless sensor network (WSN) simulation testbed, we consider 49 randomly distributed sensor nodes with random connecting distances between neighboring nodes.

## 5.1 AR and IAR Evaluation and Results

We compare our proposed AR and IAR algorithms with the following four routing algorithms: Basic Ant Routing [16], Sensor-driven Cost-aware Ant Routing [57], Flooded Piggybacked Ant Routing [57], and Flooded Piggybacked Ant Routing [57].

We constructed an event driven simulator to evaluate the performance of the al-

gorithms such as success rates, energy consumption, latency and energy efficiency as performance metrics. We run the simulation for 200 seconds having total number of 7 X 7 sensor node grid. An ant is removed from the network if it visits more than  $|N|/2$  nodes on its way to the destination. Nodes are assigned numbers between 0 and 48. Figure 5.2 shows one instance of radio connectivity model in the simulation environment with uniform sensor nodes and Figure 5.3 shows another example of radio connectivity model with random sensor nodes.

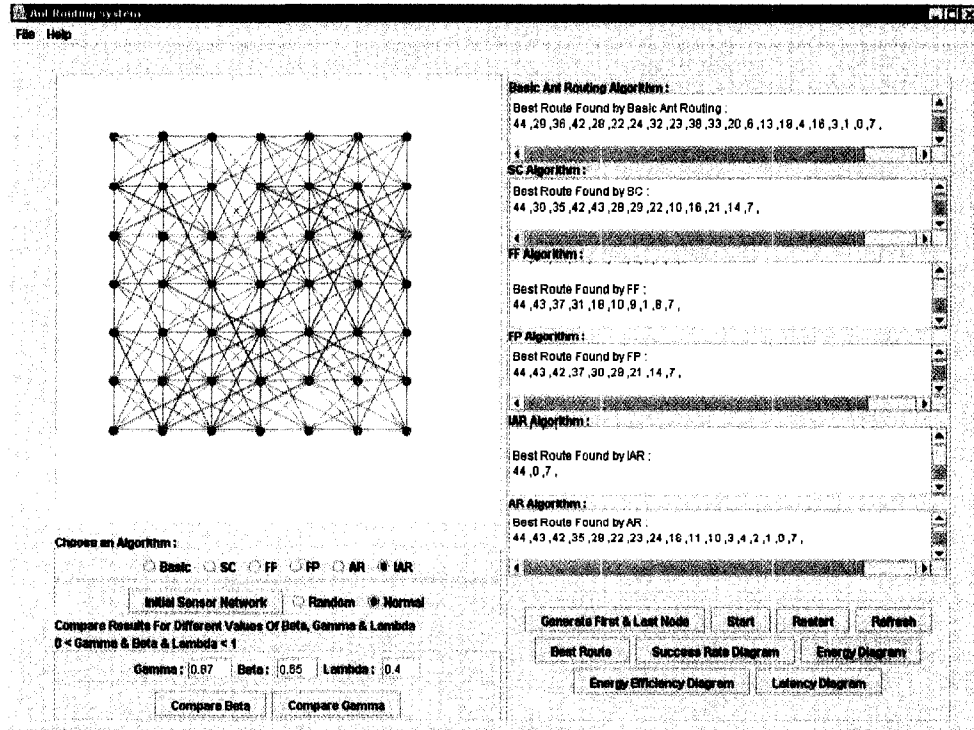


Figure 5.2: Sensor Network Environment

Figure 5.4 shows all routes traversed by forward ants between node 5 (source node) and node 8 (destination node). It is evident from this figure that selected routes only

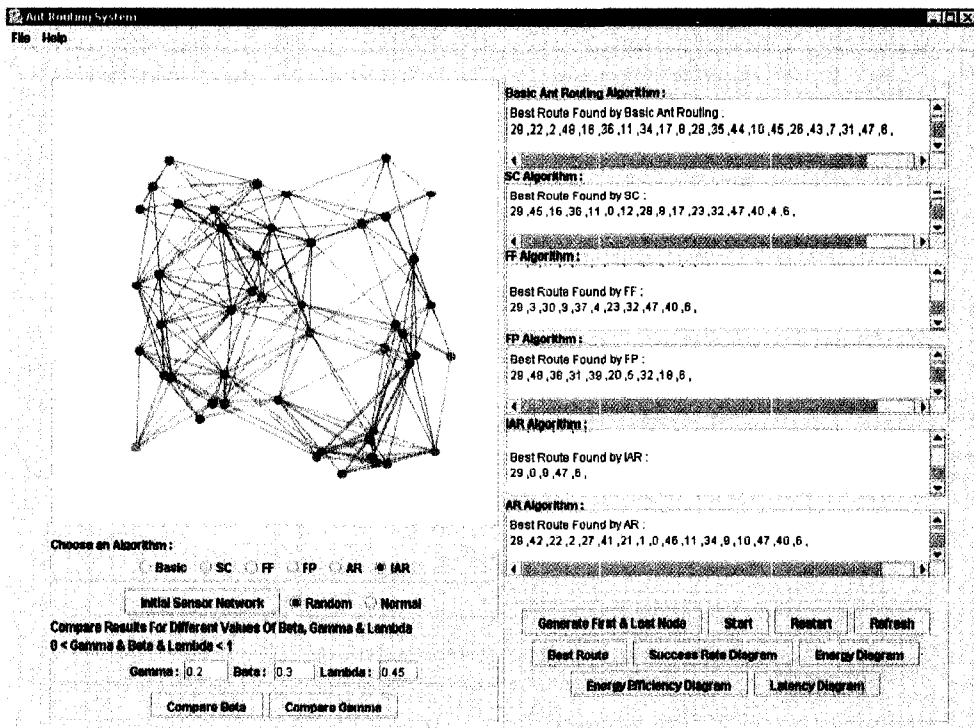


Figure 5.3: Randomized Sensor Network Environment

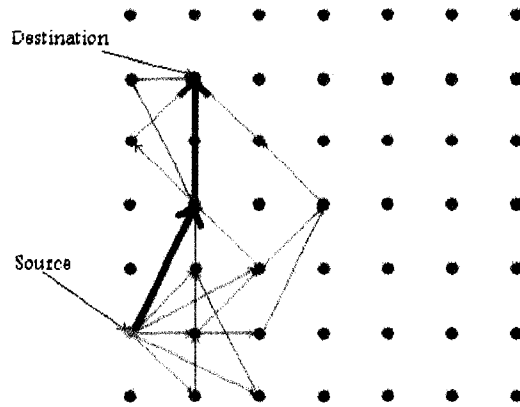


Figure 5.4: Traces of forward ant in our algorithm

contain one intermediate node; most ants move along this route and few ants select other routes. All of the packets sent by the source node are received by the destination node.

In each evaluation, we choose a value for  $\beta$ ,  $\gamma$  and  $\lambda$  between 0 and 1. We chose the increment factor of 0.1 for each of the variables and conducted the simulation. Among all the combinations of the three variables,  $\beta=0.1$ ,  $\gamma=0.5$  and  $\lambda=0.7$  resulted in optimum results that are shown in Figure 5.5, 5.6, 5.7 and 5.8.

### 5.1.1 Success rate Comparisons

Figure 5.5 shows the success rate comparison among the algorithms. Success rate is the total number of packets received at the destination vs. the total number of packets sent from the source. As shown in the figure, in the case of IAR, the success rate is almost close to 1, which means least number of packets is lost in the network. After IAR, the AR

shows better success rate in comparison with the Basic, SC, FF and the FP algorithms.

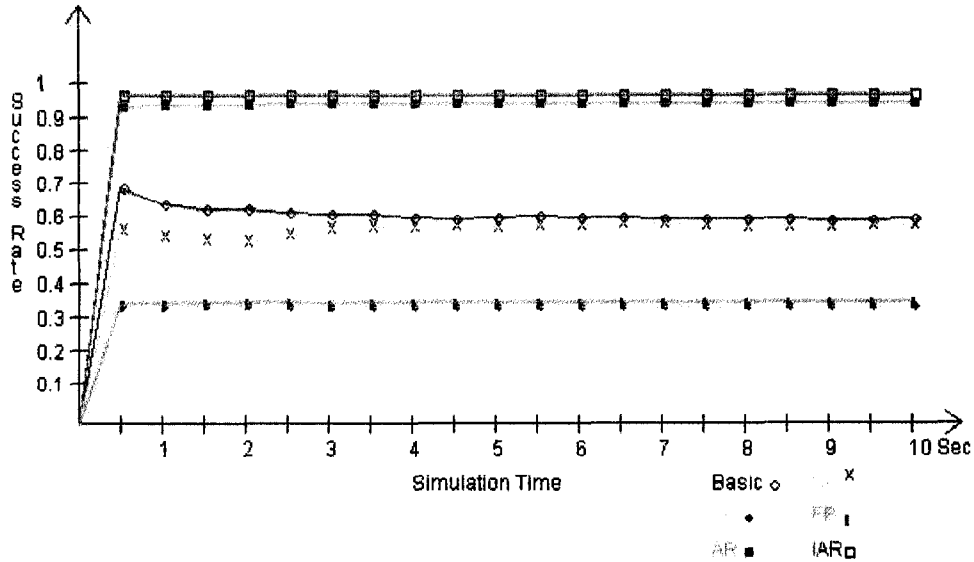


Figure 5.5: Success rates evaluation among Basic, SC, FF, FP, AR, IAR

### 5.1.2 Latency Comparisons

Figure 5.6 shows the comparison of time delay of a packet between the source and the destination (latency) using the different algorithms. We assume visiting more number of nodes in a route by a packet will result in higher latency. We assume that the time taken between any of two neighbor nodes and the processing time of packet in each sensor node are uniform. Therefore, we can ignore the time unit and calculate delay as the division of ‘number of visited nodes’ by the ‘number of routes found’, which results in ‘average number of nodes visited per each route’. As shown in Figure 5.6, in the case of IAR, the latency is the lowest, followed by the AR, the FF, the FP, the Basic and the SC respectively.

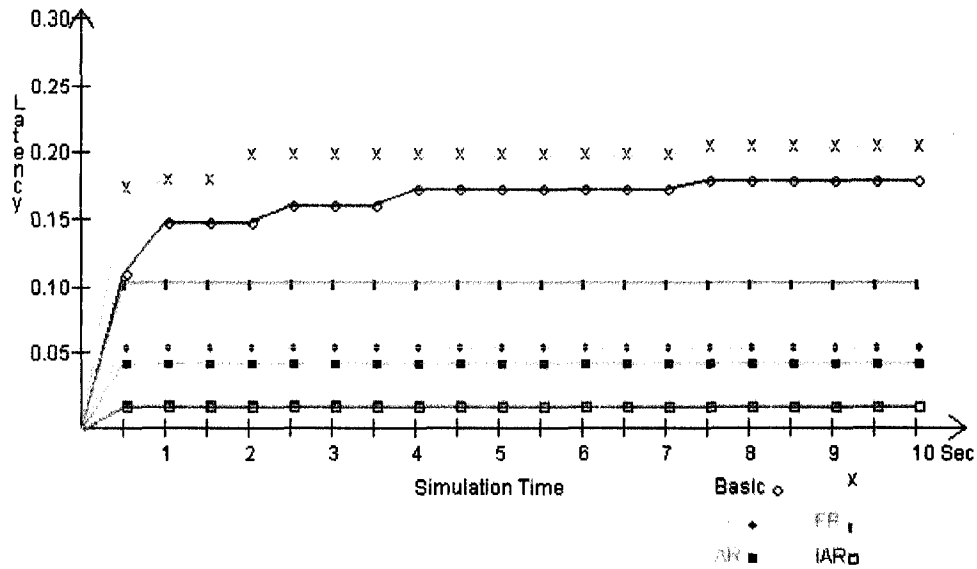


Figure 5.6: Latency evaluation among Basic, SC, FF, FP, AR, IAR

### 5.1.3 Energy Evaluations

The comparison of energy consumption among the algorithms is shown in Figure 5.7. We assume each visited sensor node consumes an energy unit. Therefore, we define the total energy consumption as equivalent to the total energy consumed for visiting a number of sensor nodes in the network. As shown in the figure, in the case of IAR, the least number of nodes are visited in the network, thereby consuming the least energy. AR consumes a bit higher energy than IAR followed by the FF, the Basic and the SC, respectively. Also note, the FP consumes the highest energy among all.

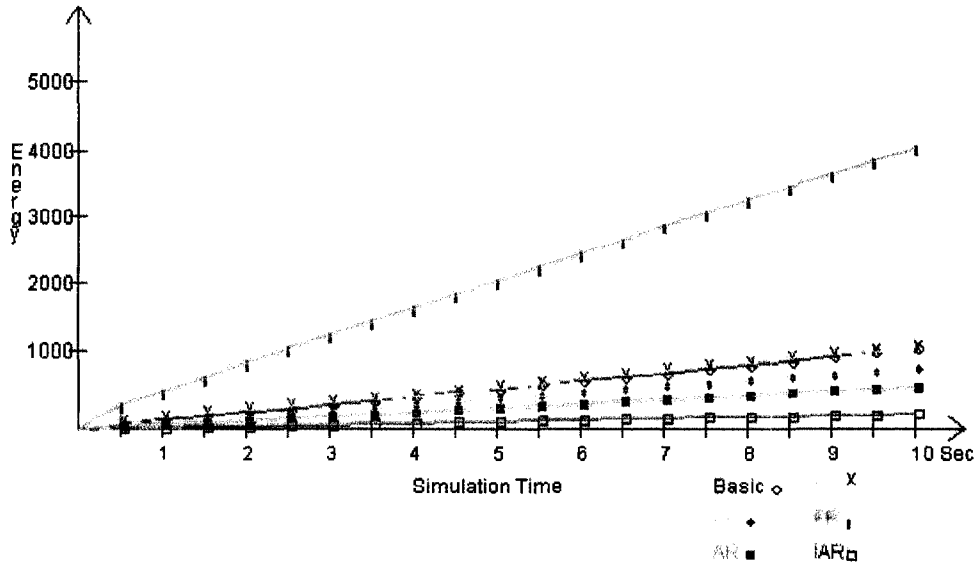


Figure 5.7: Energy evaluation among Basic, SC, FF, FP, AR, IAR

#### 5.1.4 Energy Efficiency Comparisons

The IAR algorithm also exhibits the most energy efficiency in comparison with the others. Energy efficiency is the ratio between the number of packets received at the destination and the total energy consumption in the network [57]. As shown in Figure 5.8, in the case of IAR, the energy efficiency is almost 0.32, the highest among all, which in the case of AR 0.13, for FF 0.08, for Basic 0.04, for SC 0.03 and for FP 0.01. IAR considers the distance between the neighbor sensor node and the destination sensor node while we calculate heuristic correction factor  $A_{i,d}$ . Therefore, the packets always tend to go in a route that is closer to the destination. This ensures that the number of packets sent in the network is less; the latency decreases and the success rate increases. By comparing all six algorithms in all four diagrams, the success-rate diagram, the energy diagram,

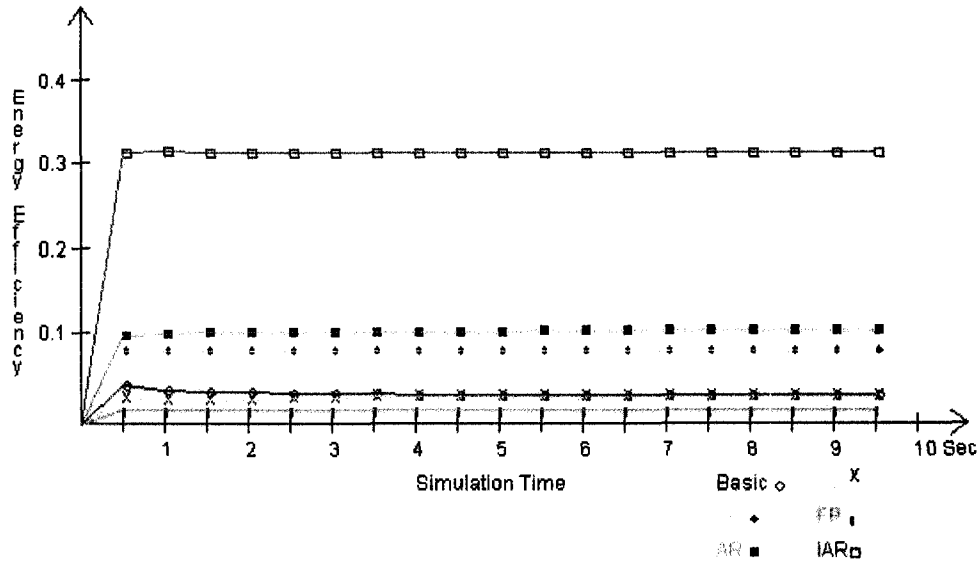


Figure 5.8: Energy efficiency evaluation among Basic, SC, FF, FP, AR, IAR

the latency diagram and the energy-efficiency diagram we saw that the proposed IAR algorithm shows better results for randomized WSNs.

## 5.2 M-IAR and MO-IAR Evaluation and Results

In the previous section, we explained the results of the proposed AR and IAR routing algorithms. In this section we are going to illustrate the performance evaluation and results of the proposed M-IAR and MO-IAR routing algorithms.

### 5.2.1 M-IAR

As a WSN simulation testbed, we consider 49 randomly distributed sensor nodes with random connecting distances between neighboring nodes. The simulation is repeated

500 times for the duration of 200 seconds each. The number of forward ants that can be sent out within this timeframe depends on the number of hops between the source and the destination. At the beginning of the simulation, the protocol assumes one of the 49 nodes as the sink node and the rest of the 48 nodes as possible source nodes. The simulation takes each node from the set of 48 nodes in turn as the source node and finds the shortest path between the sink and the source node. After each simulation, M-IAR provides all the shortest paths between each source and the sink, the end-to-end delay between them and the jitter values. One interesting feature of M-IAR is that in more than 98 percent of the test cases, it could successfully find the shortest path within the first three route discovery attempts by the forward ants. The number of visited routes by the forward ants is related to the packet number. This is due to the fact that we calculate the end-to-end delay once a  $F_{\text{ant}}$  successfully reaches the destination through any route. In this context, the end-to-end delay is taken as:

$$\text{End-to-end delay} = \sum(\text{local packet processing delay in each hop} + \text{transmission delay});$$

where, local processing takes into account the delay in calculating the probabilities of next-hop neighbors, updating the routing table, the header information and the transmission delay is the communication delay between two neighboring nodes. In one simulation the total number of packets that were lost during the simulation time is 9 and shown as a delay value of zero. This might happen in two cases. In the first case a packet is deemed non-convergent if it has already visited more than half of the sensor nodes and thus

discarded. The second might occur in case the current node does not have any neighbor node within its range i.e. no way for exit. In our simulation we find that the average end-to-end delay is 18.7 milliseconds, which shows that the protocol is capable of handling a throughput of 53 packets per second, which is computed as  $1 / \text{end-to-end delay}$ .

We measure jitter by calculating the delay variance between two successively received forward ants at the destination node. The highest frequency of jitter value is between 0 and 1 millisecond while some sporadic jitter values are seen around 15 to 18 milliseconds band.

### 5.2.2 MO-IAR

We have modified the works presented in [16], and [103] by adding our proposed many-to-one routing algorithm i.e. algorithm 7, which we explained in the previous chapter. We choose four different WSN simulation testbeds (see Figure 5.9) to evaluate MO-IAR and compared it with the Basic, SC, FF, and FP algorithms. We evaluate MO-IAR and the Basic, SC, FF, FP algorithms in terms of the total time taken to transmit data from 7 source nodes to a particular destination and the congestion observed during the routing process. In order to find the global percentage of total time taken by each algorithm, we first take each WSN shown in Figure 5.9, run each of the 4 simulations 10 times, calculate the total routing time of each algorithm for each simulation and finally, make the average of the total time.

Figure 5.10 shows the percentage of total time taken by each algorithm. The time taken by each algorithm for each WSN simulation testbed includes the 7 data ants

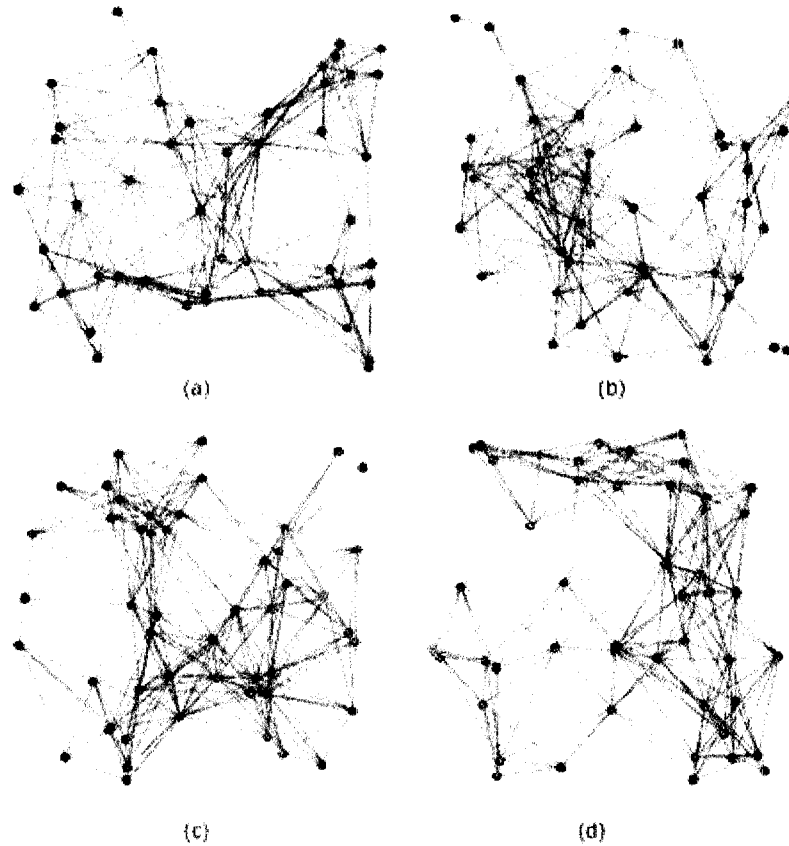


Figure 5.9: Four WSN models for evaluating MO-IAR

traveling from the source nodes to the destination by taking into account the routing time, waiting in queue, and the backoff time. From the figure, we conclude that our proposed MO-IAR algorithm requires the least amount of time (10.6 percent) in delivering the source packets to the destination.

We now illustrate the congestion scenario of the algorithms. If the shortest paths generated during phase 1 are completely disjoint in terms of common neighbor, it results in no collision. Such a situation might stem from the shortest paths shown in Figure 4.3.

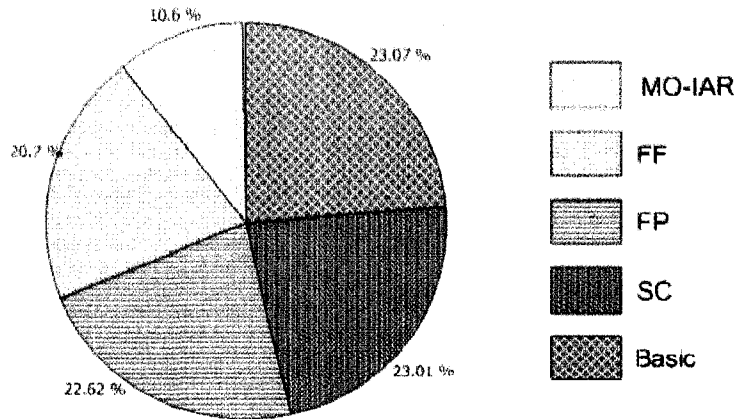


Figure 5.10: Total time taken by each algorithm during the simulation

However, the network architecture does not always ensure such a situation. Thus, we take the four WSN simulation testbeds shown in Figure 5.9 to calculate the percentage of collisions suffered by each routing algorithm. Figure 5.11 shows the percentage of collision by taking into account all four networks during the simulation time. MO-IAR suffers

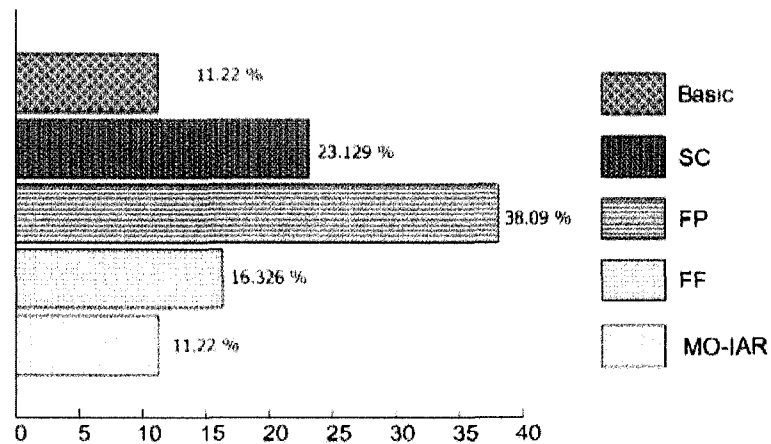


Figure 5.11: Total collisions observed by each algorithm during the simulation

lower collision than SC, FF and FP algorithms while it shows similar congestion behavior

as the Basic algorithm. This is because when we extended the Basic algorithm [16] by incorporating our proposed many-to-one approach, it came out that the Basic algorithm uses long disjoint paths. This generates a high end-to-end delay as shown in Figure 5.10 but produces relatively less congestion. On the other hand, MO-IAR often finds the shortest paths in such a way that some closely located neighbors share some portions of the path depending on the network connectivity. This generates the least end-to-end delay, as shown in Figure 5.10, while causing similar congestion as in the case of the Basic algorithm.

## Chapter 6

# CONCLUSIONS AND FUTURE WORK

In this thesis, we proposed four new ant-based algorithms, which are the Adaptive Routing (AR) algorithm, the Improved Adaptive Routing (IAR) algorithm, the Multimedia-enabled Improved Adaptive Routing (M-IAR) algorithm and the Many-to-One Improved Adaptive Routing (MO-IAR) algorithm for routing in WSNs.

We have used reinforcement learning features for our algorithms. These algorithms can adapt themselves to the changes in the network. For evaluating the performance of the algorithms, we compared them with the algorithms proposed in [103]. By comparing the first two proposed AR and IAR routing algorithms with the Basic Routing (Basic) algorithm, the Sensor-driven Cost-aware Ant Routing (SC) algorithm, the Flooded Forward Ant Routing (FF) algorithm, the Flooded Piggybacked Ant Routing (FP) algorithm, the AR showed good performance results, and the IAR showed the best per-

formance results in all the tested conditions. Adopting the AR and the IAR algorithm for routing in a WSN can result in low energy consumption, high-energy efficiency, less latency, and a high success rate.

The third proposed algorithm was M-IAR. It is an ant-colony based routing algorithm that is specifically tailored for delivering multimedia packets over WSN. M-IAR is optimized for tolerable end-to-end delay and jitter to be able to handle multimedia sensory data. While routing multimedia traffic, it finds the shortest path by consuming less energy, visiting less number of hops, and providing high packet success rate. M-IAR can be configured for both upstream and downstream multimedia sensory data routing.

MO-IAR, the fourth proposed algorithm in this sequence is an ant-colony based routing algorithm that is tailored for routing upstream many-to-one sensory data. The routing algorithm is coupled with a lightweight congestion control algorithm that helps in mitigating the collision. The algorithm operates in two phases. During 1<sup>st</sup> phase, it finds the shortest paths between each source node to a particular destination node, while it uses these shortest paths to avoid probable collisions during the 2<sup>nd</sup> phase. When compared with other related algorithms, MO-IAR outperforms them in terms of finding the shortest path within the least amount of overall time. The congestion behavior of MO-IAR was also satisfactory.

An interesting feature we want to investigate in the future is to incorporate the effect of dynamic network topology on the routing protocols as a result of node mobility or node failure.

# References

- [1] K. Akkaya and M. Younis. A survey on routing protocols for wireless sensor networks. *Journal on Ad Hoc Networks*, 3:325–349, June 2005.
- [2] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. A survey on sensor networks. *IEEE Journal on Communications*, 40(8):102–114, 2002.
- [3] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Journal on Computer Networks*, 38:393–422, 2002.
- [4] J. N. Al-Karaki and A. E. Kamal. Routing techniques in wireless sensor networks: a survey. *Journal on Wireless Communications*, 11:6–28, 2004.
- [5] P. Arabshahi, A. Gray, I. Kassabalidis, A. Das, S. Narayanan, M. El-Sharkawi, and R. J. Marks II. Adaptive routing in wireless communication networks using swarm intelligence. In *Inproceedings of Ninth AIAA International Communications Satellite Systems Conference, Toulouse, France, April 2001*.
- [6] B. Baran. Improved antnet routing. In *Inproceedings of the ACM SIGCOMM Computer Communication, San Jose, Costa Rica*, volume 31, pages 42–48, 2001.

- [7] B. Baran and R. Sosa. Antnet: Routing algorithm for data networks based on mobile agents. *Journal on Inteligencia Artificial, Revista Iberoamericana de Inteligencia Artificial*, 12:75–84, 2001.
- [8] E. Bonabeau, M. Dorigo, and G. Theraulaz. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford University Press, 1999.
- [9] E. Bonabeau and G. Thraulaz. Swarm smarts. In *Scientific American*, pages 72–79, March 2000.
- [10] D. Braginsky and D. Estrin. Rumor routing algorithm for sensor networks. In *Inproceedings of the First Workshop on Sensor Networks and Applications, WSNA 02, Atlanta, Georgia, USA*, pages 22–31, September 2002.
- [11] M. Britton, V. Shum, L. Sacks, and H. Haddadi. A biologically-inspired approach to designing wireless sensor networks. In *Inproceedings of the Second European Workshop on Wireless Sensor Networks, Istanbul, Turkey*, pages 256–266, February 2005.
- [12] M. Bundgaard and T. C. Damgaard. Ant routing system a routing algorithm based on ant algorithms applied to a simulated network. Technical report, IT University of Copenhagen, Denmark, 2002.
- [13] T. Camilo, C. Carreto, J. S Silva, and F. Boavida. An energy-efficient ant-based routing algorithm for wireless sensor networks. In *Inproceedings of the Fifth Inter-*

- national Workshop on Ant Colony Optimization and Swarm Intelligence, Brussels, Belgium*, pages 49–59, September 2006.
- [14] G. D. Caro and M. Dorigo. Antnet: A mobile agents approach to adaptive routing. In *Inproceedings of the First Hungarian National Conference on Agent, HUNABC '98, Brges, Belgium*.
- [15] G. D. Caro and M. Dorigo. An adaptive multi-agent routing algorithm inspired by ants behavior. In *The Fifth Annual Australasian Conference on Parallel and Real-Time Systems*, pages 261–272, 1998.
- [16] G. D. Caro and M. Dorigo. Antnet: Distributed stigmergetic control for communications networks. *Journal of Artificial Intelligence*, 9:317–365, December 1998.
- [17] K. S. Chan, H. Pishro-Nik, and F. Fekri. Analysis of hierarchical algorithms for wireless sensor network routing protocols. In *Inproceedings of the IEEE Wireless Communications and Networking Conference, WCNC, New Orleans, Louisiana, USA*, volume 3, pages 1830–1835, March 2005.
- [18] J. Chen, D. Subramanian, and P. Druschel. Ants and reinforcement learning: A case study in routing in dynamic networks. In *Inproceedings of the 15th International Joint Conference on Artificial Intelligence, IJCAI '97*.
- [19] C. Chong and S. P. Kumar. Sensor networks: Evolution, opportunities, and challenges. In *Inproceedings of the IEEE, Orlando, FL, USA*, volume 91, pages 1247–1256, August 2003.

- [20] M. Chu, H. Haussecker, and F. Zhao. Scalable information-driven sensor querying and routing for ad hoc heterogeneous sensor networks. *International Journal on High Performance Computing Applications*, 16(3):650–667, Fall 2002.
- [21] A. Colorni, M. Dorigo, and V. Maniezzo. Distributed optimization by ant colonies. In *Inproceedings of the First European Conference on Artificial Life, Cambridge, MA, USA*, pages 134–142, 1992.
- [22] D. Culler and D. E. M. Srivastava. Overview of sensor network. Technical Report 8, Technical Report, IEEE Computer Magazine, August 2004.
- [23] F. Dowla, editor. *Handbook of RF and Wireless Technologies*. Elsevier, 2004.
- [24] C. T. Ee and R. Bajcsy. Congestion control and fairness for many-to-one routing in sensor networks. In *Inproceedings of the Second International Conference on Embedded Networked Sensor Systems, Baltimore, MD, USA*, pages 148–161, November 2004.
- [25] A. P. Engelbrecht. *Fundamentals of Computational Swarm Intelligence*. Wiley, 2005.
- [26] H. Eren. *Wireless Sensors and Instruments*. CRC Press, 2006.
- [27] D. Estrin, L. Girod, G. Pottie, and M. Srivastava. Instrumenting the world with wireless sensor networks. In *Inproceedings of the International Conference on Acoustics, Speech and Signal Processing, ICASSP '01, Salt Lake City, Utah, USA*, May 2001.

- [28] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar. Next century challenges: Scalable coordination in sensor networks. In *Inproceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking, MobiCom '99, Seattle, WA, USA*, August 1999.
- [29] L. Gan, J. Liu, and X. Jin. Agent-based, energy efficient routing in sensor networks. In *Inproceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems, AAMAS '04, New York, NY, USA*, pages 472–479, August 2004.
- [30] S. Gandham, M. Dawande, and R. Prakash. An integral flow-based energy-efficient routing algorithm for wireless sensor networks. In *IEEE Wireless Communications and Networking Conference, WCNC, Atlanta, GA, USA*, August 2004.
- [31] R. Ghasemaghaei, A. M. Rahman, M. A. Rahman, W. Gueaieb, and A. El Saddik. Ant colony-based many-to-one sensory data routing in wireless sensor networks. In *Inproceedings of the ACS/IEEE International Workshop on Wireless Internet Services, WISE '08, Doha, Qatar*, April 2008.
- [32] R. GhasemAghaei, M. A. Rahman, W. Gueaieb, and A. El Saddik. Ant colony-based reinforcement learning algorithm for routing in wireless sensor networks. In *Inproceedings of the IEEE Instrumentation and Measurement Technology Conference, IMTC '07, Warsaw, Poland*, pages 1–6, May 2007.

- [33] L. G. Greenwald and H. Sethu. On scheduling sensor networks. In *Workshop on Real-Time Decision Support and Diagnosis Systems, Edmonton, Alberta, Canada*, pages 83–84, July 2002.
- [34] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. An application-specific protocol architecture for wireless microsensor networks. *IEEE Journal on Wireless Communications*, 1(4):660–670, October 2002.
- [35] W. Heinzelman, J. Kulik, and H. Balakrishnan. Adaptive protocols for information dissemination in wireless sensor networks. In *Inproceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking, MobiCom '99, Seattle, WA, USA*, August 1999.
- [36] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Inproceedings of the 33rd Hawaii International Conference on System Sciences, HICSS, Maui, Hawaii, USA*, January 2000.
- [37] W. R. Heinzelman, A. Sinha, A. Wang, and A. P. Chandrakasan. Energy-scalable algorithms and protocols for wireless microsensor networks. In *IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP '00, Istanbul, Turkey*, volume 6, pages 3722–3725, June 2000.
- [38] M. Heusse, S. Gu'erin, D. Snyers, and P. Kuntz. Adaptive agent-driven routing and load balancing in communication networks. In *Inproceedings of the ANTS '98*.

- [39] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. E. Culler, and K. S. J. Pister. System architecture directions for networked sensors. In *ACM SIGPLAN*, volume 35, pages 93–104, November 2000.
- [40] M. Hollick, I. Martinovic, T. Krop, and I. Rimac. A survey on dependable routing in sensor networks, ad hoc networks, and cellular networks. In *Inproceedings of the Thirty EUROMICRO Conference, EUROMICRO 04, Rennes, France, September 2004*.
- [41] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Inproceedings of the Sixth Annual International Conference on Mobile Computing and Networks, Boston, MA, USA, August 2000*.
- [42] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, and F. Silva. Directed diffusion for wireless sensor networking. *IEEE/ACM Journal on Networking*, 11(1):2–16, 2003.
- [43] M. T. Islam, P. Thulasiraman, and R. K. Thulasiram. A parallel ant colony optimization algorithm for all-pair routing in manets. In *Inproceedings of the 17th International Parallel and Distributed Processing Symposium, IPDPS03, Nice, France, April 2003*.
- [44] L. P. Kaelbling, M. L. Littman, and A. W. Moore. Reinforcement learning: A survey. *Journal of Artificial Intelligence Research*, 4:237–285, 1996.

- [45] H. Karl and A. Willig. *Protocols and Architectures for Wireless Sensor Networks*. Wiley, 2005.
- [46] H. Karl and A. Willig. A short survey of wireless sensor networks. Technical report, November 2003.
- [47] B. Karp and H. T. Kung. Gpsr: Greedy perimeter stateless routing for wireless networks in proc. 6th int'l conf. on mobile computing and networks. In *Inproceedings of the Sixth Conference on Mobile Computing and Networks ,ACM Mobicom, Boston, MA, USA, 2000*.
- [48] I. Kassabalidis, M. A. El-Sharkawi, R. J. Marks II, P. Arabshahi, and A. A. Gray. Swarm intelligence for routing in communication networks. In *Inproceedings of IEEE Global Telecommunications, GLOBECOM '01, San Antonio, TX, USA, volume 6, February 2001*.
- [49] I. N. Kassabalidis, M. A. El-Sharkawi, R. J. Marks II, P. Arabshahi, and A. A. Gray. Adaptive-sdr: Adaptive swarm-based distributed routing. In *Inproceedings of the International Joint Conference on Neural Networks, IJCNN '02, Honolulu, HI, USA, volume 1, pages 351–354, May 2002*.
- [50] I. Khemapech, I. Duncan, and A. Miller. A survey of wireless sensor networks technology. In *Inproceedings of the sixth Annual PostGraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, PGNET '05, Liverpool, UK, pages 425–430, July 2005*.

- [51] B. Krishnamachari, D. Estrin, and S. Wicker. Modelling data-centric routing in wireless sensor networks. In *Inproceedings of the IEEE INFOCOM, New York, NY, USA*, June 2002.
- [52] V. Kumar. Sensor: The atomic computing particle. In *Inproceedings of the ACM Sigmod Record, San Diego, California, USA*, volume 32, pages 16–21, December 2003.
- [53] M. Kuorilehto, M. Hannikainen, and T. D. Hamalainen. A survey of application distribution in wireless sensor networks. *Journal on Wireless Communications and Networking, EURASIP*, 5:774–788, June 2005.
- [54] S. Lindsey and C. S. Raghavendra. Pegasus: Power efficient gathering in sensor information systems. In *Inproceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA*, March 2002.
- [55] S. Lindsey, C. S. Raghavendra, and K. Sivalingam. Data gathering in sensor networks using the energy delay metric. In *Inproceedings of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing, San Francisco, CA, USA*, April 2001.
- [56] Y. Liu and K. M. Passino. Swarm intelligence: Literature overview. Technical report.

- [57] Y. Lu, G. Zhao, and F. Su. Adaptive ant-based dynamic routing algorithm. In *Inproceedings of the Fifth World Congress on Intelligent Control and Automation, Hangzhou, China, June 2004*.
- [58] I. Mahgoub M. Ilyas. *Smart Dust: Sensor Network Applications, Architecture and Design*. CRC Press, 2006.
- [59] A. Manjeshwar and D.P. Agrawal. Teen: A routing protocol for enhanced efficiency in wireless sensor networks. In *Inproceedings of the First International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, San Francisco, CA, USA, April 2001*.
- [60] A. Manjeshwar and D.P. Agrawal. Apteem: a hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks. In *Inproceedings of the Second International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile computing, Ft. Lauderdale, FL, USA, April 2002*.
- [61] D. Marco, E. J. Duarte-Melo, M. Liu, and D. L. Neuhoff. On the many-to-one transport capacity of a dense wireless sensor network and the compressibility of its data. In *Inproceedings of the Second International Workshop on Information Processing in Sensor Networks, IPSN '03, Palo Alto, CA, USA, April 2003*.
- [62] O. Moussaoui and M. Nami. A distributed energy aware routing protocol for wireless sensor networks. In *The Second ACM International Workshop on Performance*

*Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks, PE-WASUN, Montreal, Quebec, Canada, October 2005.*

- [63] R. Muraleedharan and L. Osadciw. Sensor communication network using swarm intelligence. In *Inproceedings of the Second IEEE Upstate New York Networking Workshop, Syracuse University, Syracuse, NY, USA, October 2003.*
- [64] R. Muraleedharan and L. A. Osadciw. A predictive sensor network using ant system. In *Inproceedings of the SPIE Aerosense, Orlando, FL, USA, April 2004.*
- [65] C. S. R. Murthy and B. Manoj. *Ad Hoc Wireless Networks: Architectures and Protocols.* Prentice Hall, 2004.
- [66] J. S. Oh, S. Bae, J. Ahn, and S. Kang. Route reinforcement for efficient qos routing based on ant algorithm. In *International Conference on Information Networking, ICOIN 04, Busan, Korea, February 2004.*
- [67] K. Oida and M. Sekido. An agent-based routing system for qos guarantees. In *Inproceedings of the IEEE International Conference on Systems, Man, and Cybernetics, SMC '99, Tokyo, Japan, October 1999.*
- [68] C. E. Perkins and E. M. Royer. Ad-hoc on-demand distance vector routing. In *Mobile Computing Systems and Applications, WMCSA '99, New Orleans, LA, USA, pages 90–100, February 1999.*
- [69] N. N. Pham, J. Youn, and C. Won. A comparison of wireless sensor network routing protocols on an experimental testbed. In *Inproceedings of the IEEE International*

*Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, SUTC 06, Taichung, Taiwan, June 2006.*

- [70] S. Phoha, T. F. L. Porta, and C. Griffin, editors. *Sensor Network Operations*. Wiley, May 2006.
- [71] M. A. Rahman, R. GhasemAghaei, A. El Saddik, and W. Gueaieb. M-IAR: Biologically inspired routing protocol for wireless multimedia sensor networks. In *IEEE International Instrumentation and Measurement Technology Conference, I2MTC '08, Victoria, Vancouver Island, British Columbia, Canada, May 2008*.
- [72] E. M. Royer and C. Toh. A review of current routing protocols for ad hoc mobile wireless networks. In *IEEE Personal Communications*, April 1999.
- [73] H. G. Sandalidis, C. X. Mavromoustakis, and P. Stavroulakis. Ant based probabilistic routing with pheromone and antipheromone mechanisms. *International Journal on Communication Systems, IJCS*, 17:55–62, January 2004.
- [74] R. Schoonderwoerd, O. E. Holland, J. L. Bruten, and L. J. M. Rothkrantz. Ant-based load balancing in telecommunications networks. *Journal on Adaptive Behavior*, 5(2):169–207, 1996.
- [75] C. Schurgers and M. Srivastava. Energy efficient routing in wireless sensor networks. In *Inproceedings of the IEEE MILCOM, Washington, D.C., USA, October 2001*.
- [76] C. Shen and C. Jaikaeo. Ad hoc multicast routing algorithm with swarm intelligence. *Journal on Mobile Networks and Applications, MONET*, 10:47–59, 2005.

- [77] K. M. Sim and W. H. Sun. Ant colony optimization for routing and load-balancing: Survey and new directions. *IEEE Journal on Systems, Man, and Cybernetics, Part A*, 33(5), September 2003.
- [78] G. Singh, S. Das, S. V. Gosavi, and S. Pujar. *Recent Developments in Biologically Inspired Computing*. Idea Group Publishing, 2005.
- [79] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie. Protocols for self-organization of a wireless sensor network. *IEEE Journal on Personal Communications*, 7(5):16–27, 2000.
- [80] K. Sohraby, D. Minoli, and T. Znati. *Wireless Sensor Networks: Technology, Protocols, and Applications*. Wiley, March 2007.
- [81] V. Soto-Hernandez and A. Weitzenfeld. Ant colony algorithm for swarm systems. In *Inproceedings of the Third IEEE Latin American Robotics Symposium, LARS '06, Santiago, Chile*, pages 74–79, October 2006.
- [82] I. Stojmenovic, editor. *Handbook of Sensor Networks: Algorithms and Architectures*, volume 49. Wiley-Interscience, September 2005.
- [83] Z. Subing and L. Zemin. A qos routing algorithm based on ant algorithm. In *IEEE International Conference on Communications, ICC '01, Helsinki, Finland*, volume 5, pages 11–14, June 2001.

- [84] L. Subramanian and R. H.Katz. An architecture for building self configurable systems. In *Inproceedings of the IEEE/ACM Workshop on Mobile Ad Hoc Networking and Computing, Boston, MA, USA, August 2000*.
- [85] R. S. Sutton and A. G. Barto. *Reinforcement Learning: An Introduction*. MIT Press, Cambridge, MA, USA, March 1998.
- [86] Andrew S. Tanenbaum. *Computer Networks*. Prentice Hall PTR, March 2003.
- [87] S. Tilak, N. Abu-Ghazaleh, and W. Heinzelman. A taxonomy of wireless microsensor network models. In *ACM Mobile Computing and Communications Review, MC2R '02, Fort Worth, TX, USA, volume 6, pages 28–36, April 2002*.
- [88] M. Tubaishat and S. Madria. Sensor networks: An overview. Technical Report 2, IEEE Potentials, 2003.
- [89] N. Vlahic and D. Xia. Wireless sensor networks: To cluster or not to cluster? In *Inproceedings of the International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM '06, Niagara-Falls, Buffalo-NY, USA, June 2006*.
- [90] N. Wakamiya, Y. Ohtaki, M. Murata, and M. Imase. A biologically-inspired data-centric communication protocol for sensor networks. In *Inproceedings of the First International Conference on Distributed Computing in Sensor Systems, DCOSS '05, Marina del Rey, CA, USA, June 2005*.

- [91] Z. Wang and J. Crowcroft. Quality-of-service routing for supporting multimedia applications. *IEEE Journal on Selected Areas in Communications*, 14(7), September 1996.
- [92] T. White, B. Pagurek, and F. Oppacher. Connection management using adaptive mobile agents. In *Inproceedings of the International Conference on Parallel and Distributed Processing Techniques and Applications, PDPTA '98, Las Vegas, NV, USA*, July 1998.
- [93] Y. Xiao, editor. *Security in Sensor Networks*. Auerbach, 2007.
- [94] Y. Xu, J. Heidemann, and D. Estrin. Geography-informed energy conservation for ad-hoc routing. In *Inproceedings of the seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking, ACM MobiCom, Rome, Italy*, 2001.
- [95] F. Ye, H. Luo, J. Cheng, S. Lu, and L. Zhang. A twotier data dissemination model for largescale wireless sensor networks. In *Inproceedings of Eighth Annual International Conference on Mobile Computing and Networking, MOBICOM '02, Atlanta, Georgia, USA*, September 2002.
- [96] F. Ye, G. Zhong, S. Lu, and L. Zhang. Gradient broadcast: A robust data delivery protocol for large scale sensor networks. *Journal on Wireless Networks*, 11(3):285–298, 2005.

- [97] L. Yong, Z. Guang-zhou, S. Fan-jun, and L. Xiao-run. Adaptive swarm-based routing in communication networks. *Journal of Zhejiang University SCIENCE*, 2004.
- [98] M. Younis, P. Munshi, and E. Al-Shaer. Architecture for efficient monitoring and management of sensor networks. In A. Marshall and N. Agoulmine, editors, *Inproceedings of the Sixth IFIP/IEEE International Conference on Management of Multimedia Networks and Services, MMNS '03, Belfast, Northern Ireland, UK*, September 2003.
- [99] M. Younis, M. Youssef, and K. Arisha. Energy-aware routing in cluster-based sensor networks. In *Inproceedings of the Tenth IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, MASCOTS '02, Fort Worth, TX, USA*, October 2002.
- [100] Y. Zhang and M. Fromherz. Constrained flooding: A robust and efficient routing framework for wireless sensor networks. In *Inproceedings of the 20th International Conference on Advanced Information Networking and Applications, AINA 06, Vienna, Austria*, April 2006.
- [101] Y. Zhang and M. Fromherz. Search-based adaptive routing strategies for sensor networks. In *AAAI Sensor Network Workshop, San Jose, CA, USA*, July 2004.
- [102] Y. Zhang and Q. Huang. A learning-based adaptive routing tree for wireless sensor networks. In *Inproceedings of the IEEE Third Consumer Communications and*

*Networking Conference, Las Vegas, NV, USA, January 2006.*

- [103] Y. Zhang, L. D. Kuhn, and M. P. J. Fromherz. Improvements on ant routing for sensor networks. In *International workshop on Ant Colony Optimization and Swarm Intelligence, Ants '04, Brussels, Belgium, September 2004.*
- [104] S. Ziane and A. Mellouk. A swarm intelligent multi-path routing for multimedia traffic over mobile ad hoc networks. In *Inproceedings of the First ACM International Workshop on Quality of Service and Security in Wireless and Mobile Networks, Q2SWinet 05, Montreal, Quebec, Canada, October 2005.*