Hopping: A Bidirectional Stigmergy Power Efficient On-Demand Driven Ad Hoc Routing Protocol for Wireless Sensor Networks

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A dissertation submitted to the University of Dublin,
in partial fulfillment of the requirements for the degree of
Master of Science in Computer Science

September 2006

Declaration

I declare that the work described in this dissertation is, except where otherwise stated, entirely my own work and has not been submitted as an exercise for a degree at this or any other university.

Signed: ____________________

Ricardo Simon Carbajo

11th September 2006

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Acknowledgements

First of all, I would like to thank my supervisor Meriel Huggard, she has been there when I needed, she has opened my mind and it has been a pleasure working with her.

Besides, I would like to thank Dr. Ciaran Mc Goldrick and Mathieu Robin for providing me with their advice.

In the family environment I want to thank, not only my family (mother, father, brother, sister, aunts, grandmothers and uncles) who has been supporting me during all this Msc process and encouraging me to keep going, but also the people I know in Ireland, specially my Irish family who has been very close to me.

Finally, I can not forget the whole of NDS class with whom I have lived an amazing experience, academically and personally, and where I have made good friends.

Abstract

According to Bell's Law, it emerges a new technology every ten years. In February 2003, the MIT identified the top ten emerging technologies that will change the world; Wireless Sensor Networks (WSN) was the first one.

Wireless Sensor Networks appear like a favorite candidate to create a new era of information in which everything will be controlled by sensors monitoring the environment and acting appropriately; all of that to facilitate our modern living.

It is a new technology based in sensors communicating wirelessly with each other and sensing data from the environment to processing units. If this technology is combined with Artificial Intelligence it is believed that worldwide auto-organized networks will control everything.

Because the communication is an important issue of WSN, the aim of this project has been focused on the improvement of ad hoc protocols which suite the needs and constraints of this technology. Research has been done over the area, concerning about differences with respect to traditional wired networks. Besides, it has been examined previously created ad hoc protocols for WSN.

After all the research process, keeping in mind the features of WSN, it has been developed a new protocol which addresses constraints like power and storage limitations, guaranteeing bidirectional communication between nodes. It is thought this protocol will improve the communication in WSN, avoiding hierarchy schemas, with nodes communicating with each other in an ad hoc basis paradigm to create self-organized colonies; all of this in an efficient way, with a low energy consumption and minimum data storage.

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Chapter 1 – Introduction

According to Bell's Law, it emerges a new technology every ten years. In February 2003, the MIT identified the top ten emerging technologies that will change the world; Wireless Sensor Networks (WSN) was the first one.

Experts presume it is going to be a new era of information, leaded by sensors acting and retrieving data in all different types of environments, from a house to a volcano three kilometers meter high.

These sensors, which can have mobility, will have the capacity to communicate wirelessly each other forming networks which will control an area, a country or even the world.

Taking profit of the Internet infrastructure combined with Wireless Sensor Networks everyplace will be reachable and monitored.

Besides, if Artificial Intelligence is combined with this infrastructure, it could be created self-managed networks which monitor, analyze and take decisions for the benefit of the human being.

It could sound like science fiction but it is believed it can be a reality and in fact, in the actual world are examples that indicate so. Intelligent Buildings completely equipped with sensors which tell when a fire is produced is just an example of the daily life with sensors but if you add the power of wireless to reach any place and the capacity of a sensor device to act as a processing unit which have enough autonomy to join networks, then new potential possibilities are open.

After assisting lectures about the topic, reading articles in Internet and the dissertation from Karsten Fritsche titled: "TinyTorrent: Combining BitTorrent and SensorNets" [1], I became really interested in Wireless Sensor Networks. I started to do research in how it works, possible applications, which groups are working on it, what systems are leading the panorama and mainly what needs or possibilities are offered.

In between what I found it took my attention that organizations as important as the Defense Advance Research Projects Agency (DARPA), creators of the Internet, are one of the main groups developing the idea. Besides, Intel in collaboration with the University of California, Berkeley have founded a group which is leading the area of WSN with its open source operating system, designed to address the features and constraints of this type of networks (WSN), called TinyOS [2]. This new operating system is entirely built using a new programming language based on C but with a component based event-driven paradigm, called nesC.

Furthermore the hardware being used for sensing it is composed by two units, the sensing devices (sensor) and the device in charge of processing and communications (mote). There are some producers of this hardware, and different type of motes with different sizes are being developed but for academic purposes the MICA2 motes from the Crossbow Technologies [3] are the most used and they have been used in this project.

After spending sessions learning how to program motes, using TinyOS, learning the new programming language and the new programming structure, getting hardware errors, compiling and testing all different applications that TinyOS provides, I started to figure out what attracted me the most and what is needed in WSN at the moment. At the beginning I thought about security issues, as TinyOS have already created a secure layer which does not guarantee security 100% in the vulnerable wireless medium. Finally I decided to go for the area of ad hoc routing protocols in WSN. As I was testing applications which included an existing routing layer developed in TinyOS, I got a good understanding of the needs and constraints of the routing protocols in WSN. At the moment the existing routing protocol is based on a tree-based hierarchy where the motes send data through to reach the base mote where the data is processed. The flow goes in one direction and the motes use mechanisms to discover neighbours and estimation techniques to identify the shortest path to the base mote.

One of the main concerns for the motes is the battery life; it can last about 6 to 12 months, depending on the processing activity and the communication rate. According to studies, thousands of computing operations consume the same amount of energy as one message sent. Because of that the idea was to minimize the number of messages needed in all the phases of the routing protocol; in the existing protocol, every 20 seconds a broadcast discovery message is sent to identify the neighbours.

After all of that and studying different ad hoc routing protocols like rumor based and stigmergy techniques, the protocol (hopping) was designed. The protocol try to address constraints of battery life by reducing the number of messages being sent and all of that considering the limited resources of the motes. Besides, it was thought applying stigmergy could be a good idea; the paths between motes are created by modifications in the environment, it is said in every mote which is part of a well established path, it will be an entry for this path which indicates who the sender is and where it should be sent the message.

In the rest of the document it will be explained in detail what technology is currently being used in Wireless Sensor Networks, hardware and software. It will be described the main routing algorithms which inspired the creation of the protocol. An analysis and good description of the routing layer in TinyOS will be made and the protocol in details will be described. Finally it will be commented what technology has been used and the process of implementation and debugging of the algorithm, making an evaluation of it; conclusions and future research will be stated to finish.

Chapter 2 – Introduction to Wireless Sensor Networks (WSN)

2.1- SensorNet Vision

We are leaving in the world of information where data is available to everybody but obtaining the data which is needed at a certain time is a mayor deal. In order to get the best advantage, the data should come from different sources of interest and relationships should be established to transform it in what is called information.

There are several ways of getting data from the environment but the most well known technique is called "monitoring". The process of monitoring according to [4] involves observing a situation for any changes which may occur over time, using a monitor or a measuring device. This measuring device is what we call sensor; any instrument that can retrieve diverse type of data like temperature, humidity, pressure, flow, length, speed, sound, light… and transform into an electronic data which can be processed or retransmitted.

These sensors are everywhere at the moment, from houses to companies or even roads but there are some limitations, they usually depends on powered processing systems and have to be wired to them. These constraints limit the monitoring process to certain environment with specific conditions.

According to Moore's Law (posited by Intel founder Gordon Moore in 1965) [5], the number of transistors on a chip roughly doubles every two years, resulting in more features, increased performance and decreased cost per transistor. Not only the devices have more powerful processing and are cheaper but also they provide new features like wireless communication combined with a very small size.

Because of that, it is being created a new class of monitoring systems which can get a wide range of diversity data that can be converted into a new generation of information, rich in semantic content.

Quoting [5], "These inexpensive, low-power communication devices can be deployed throughout a physical space, providing dense sensing close to physical phenomena, processing and communicating this information, and coordinating actions with other nodes. Combining these capabilities with the system software technology that forms the Internet makes it possible to instrument the world with increasing fidelity”.

David Culler et al [5] state that because of the fact that the world of computing is becoming throw the high processing and miniaturization, there is a new revolution emerging in the form of small cheap devices capable of processing and communicate wirelessly, that can be spread in any environment and interact, not only each other forming networks, but also with the Internet, in order to monitor the world and act accordingly.

All this new technology is what is emerging and is what is known as Wireless SensorNet; collection of interconnected devices with sensing, processing and communication capabilities which can retrieve many types of data, auto-organising and behave in a ubiquitous way.

The wireless sensor network regime is characterized by some constrains like limited hardware capabilities, limited energy resources and concurrent data flows which lead to a mandatory change or adaptation from the actual technology vision. Because of the limitations in hardware and power, key concepts like programming paradigms, OS, networking, data management, security, etc…, should be addressed with special constrains too.

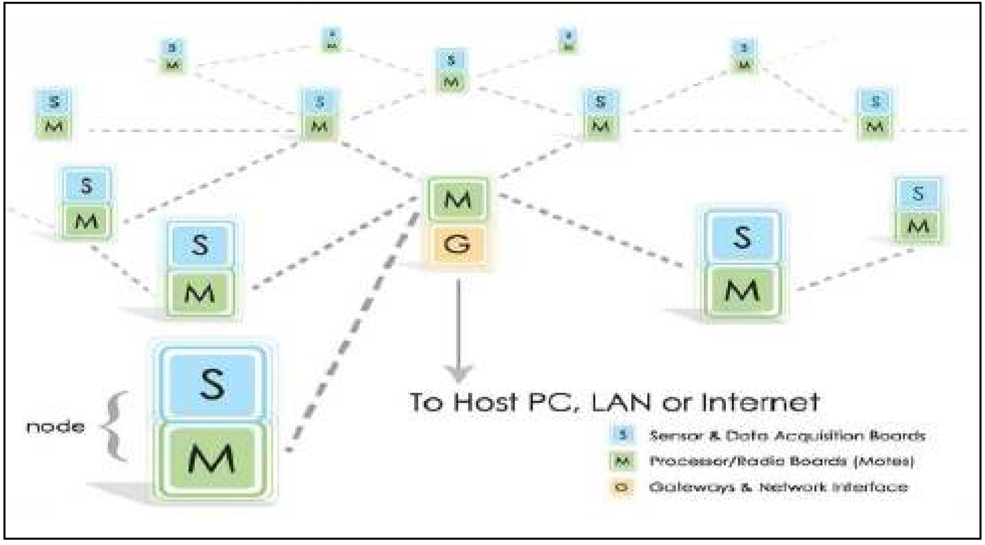
In the nearest future, this technology could generate nets all over the planet that will watch from what the people buy at the supermarkets to malicious people. If we put together this technology with the new advances in Artificial Intelligence it could be created networks of sensors with complex intelligence.

2.2- What is a Wireless Sensor Network?

A Wireless Sensor Network is a set of tiny, battery-powered sensing devices which are usually called “motes” or “smart dust”.

Typically these motes are spread in groups all over a certain physical environment. Once they are positioned, they start to connect each other wirelessly and organize them into a network (see Figure 2.1). Each mote has a radio area and all the nodes on the area are considered neighbours. Using the neighbours and ad hoc routing protocols (the motes can have mobility), the sensor starts to retrieve data from the environment (light, temperature, vibration…) and provides it to the mote unit which will manage the processing, wrapping of the messages and communication with the neighbours in order to send the data through the different motes over the network in order to reach the base node. The base node is a special mote, because it is connected to a processing station, usually traditional computers, where the data from the motes in the network is analyzed, making possible the creation of a picture of the environment in real time as well as the publication of the information in the Internet.

Retrieving data from the environment is the most frequent use for WSN although the interaction with the motes from the computer and even from the Internet is being developed; new protocols are needed to communicate in both directions.


S
M
G
node
To Host PC, LAN or Internet
S Sensor & Data Acquisition Boards
M Processor/Radio Boards (Motes)
G Gateways & Network Interface
Figure 2.1: Wireless Sensor Network [5]

2.3- What is a mote?

Typically a mote is a little device whose main tasks are: to sense (with the sensor attached to the mote), to compute and to communicate. According to that, motes have three main components:

- Microprocessor: process the data.
- Microelectromechanical systems (MEMS): provide arrays of sensory measures.
- Low-power Radios (transceivers): wireless communication.

There are many types, depending on the fabricant, with different forms and sizes. In Table 2.1, it can be seen different types of motes with its specifications used in researching with the TinyOS operating system (see Section 2.6).

Besides, depending on the type of mote, standard consumer AA or coin-style batteries keep motes “alive” for six months to a year, although new research is being doing on that using new energy sources like the solar one.

Common design constraints include:

- power conservation
- compact form
- limited memory
- limited storage capacity

Moreover, and according to [6], motes must be reasonably economical to be suitable for practical applications. Fortunately, microprocessors, sensors and RF transceivers can be inexpensively produced in large quantities using conventional semiconductor manufacturing techniques. Several species of motes based on prototypes developed by Intel and the University of California at Berkeley have recently become commercially available at $50 to $100 (U.S.) each. Researchers at Intel expect that, with re-engineering, Moore’s Law and volume production, motes could drop in price to less than $5 each over the next several years.

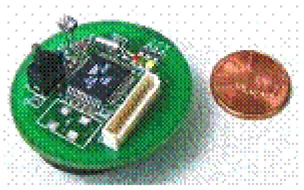
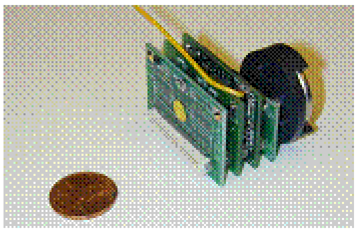
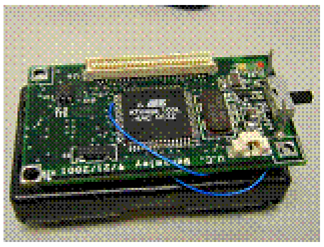
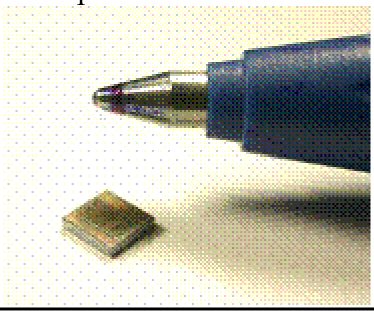
The weC Node 	The weC node was developed in the Fall of 1999 by researchers at UC Berkeley. It containes 8K of program memory and just 512 bytes of memory. On-board temperature and light data could be wirelessly communicated over it 9600 baud on-off keyed radio. An internal antenna provided a range of up to 15 feet.
The Rene Node 	Developed in the summer of 2000, Rene node expanded on the capabilities of the weC node by increasing available program and data storage. Additionally, it provided a 51-pin expansion interface that allow for connections to both analog and digital sensors. As a development platform, hundreds of sensor boards have been designed to interface to the Rene node. It is equipped with 8K of program memory, 32K of EEProm and is capable of being reprogrammed over the radio link. It communicates at 19,200 via an on-off keyed 916 Mhz radio. An external antenna allows for a communication rage of up to 100 feet.
The DOT Node	Developed in the summer of 2001, Dot shrunk the capabilities of the Rene node into a compact 1" node. A complete node including sensor, computation, communication, and a battery fit in a package the size of four stacked quarters. It was unveiled at the 2001 Intel Developers Forum in as the cornerstone of an 800 node demonstration network. The Dot platform had 16 KB of program memory and 1 K of data memory. It had the same communication capabilities of the Rene platform.
The Mica Node 	The Mica node was developed as the foundation of the NEST (Network Embedded Systems Technology) project under DARPA (Defense Advanced Research Projects Agency). Designed to facilitate the exploration of wireless sensor networking, it has been used by over 200 different research organizations. Mica contains the same expansion bus as the Rene node allowing it to utilize all existing sensor boards. The Mica node increases the radio communication rate to 40 Kbps though using specialized hardware accelerators and amplitude-shift-keying. Mica includes 128 Kbps of program memory and 4 K of data memory. It is capable of being radio-reprogrammed and has a line-of-sight rage of over 100 feet. Mica has been used in applications ranging from military vehicle tracking to remote environmental monitoring.
The Spec Node 	Spec was designed in the fall of 2002 by Jason Hill to be a highly integrated, single-chip wireless node. The CPU, memory, and RF transceiver are all integrated into a single 2.5x2.5mm piece of silicon. Fabricated by National Semiconductor, it was successfully demonstrated in March of 2003. Spec contains specialized hardware accelerators designed to improve the efficiency of multi-hop mesh networking protocols. Additionally, in includes an ultra-low power transmitter that drastically reduces overall power consumption. Spec represents the future of embedded wireless networking.

Table 2.1: Different type of motes used in TinyOS research [7]

2.4- Characteristics of a Wireless Sensor Network

According to [1] WSN research is gaining popularity, due to the exciting possibilities it opens up to new application domains. Because of that, in this section will be discussed the strengths of WSN, which give rise to these new possibilities, and the weaknesses and constraints.

2.4.1- Strengths

- **Harsh environmental conditions**: The fact that WSN work wirelessly makes possible the communication under any environmental circumstance. Besides if we add that the motes (sensors) are characterized by its reduced size, the possibilities of reaching small inaccessible places hugely increase. Furthermore with the advances in technology, motes will be as small as one of these little letters you are reading now, with enough computing process to sense, analyze and send data, and all of that powered by batteries combined with solar energy that will last months or years. Then everything, everywhere will be monitored.

- **Low Cost and High Production Volumes**: In modern industry, the large volume of production for electronic devices, minimize the cost per unit extremely. Motes are composed of microcontrollers, sensors and radio devices which can be developed easily and quickly but in order to reduce its cost, the volume of production must be huge. Although now the price of motes is not expensive (depends on model), the cost of spreading hundreds of motes all over an environment is high; if the technology is consolidated, the amount of production will increase severely, reducing the size of motes and the price will go down to some cents per unit being able to spread thousands of motes with a lower cost. Spreading more motes by surface will increase the reliability in the system and the measured data would be more accurate.

- **Ad-hoc Deployment**: Because of the nature of this technology, motes could be spread in environments without an already created topology and with mobility. Consequently WSN need the deploying of ad hoc protocols which provide communication among the motes to create auto-organized networks, discovering neighbours and gateways. This is one of the main interesting points and it is currently being done a lot of research; already existing ad hoc protocols have to be adapted to address the constraints of this technology. In this dissertation is developed an ad hoc protocol which addresses some of this constraints.

- **Fault Tolerance**: The fact that motes are hardware which works with events and concurrency in an autonomous way with radio communication makes the system lean to failures. To prevent that it has been developed software mechanisms to avoid or recover from failures (not pure recovery mechanisms in nodes but it is based on resetting); besides, if the concentration of motes in the same surface is higher, that will make the system fault tolerant; more motes could monitor and communicate data of similar conditions so the failure of a node will not produce a network system failure.

- **Data Quality**: Redundancy makes the system fault tolerance but also makes the data more reliable and consequently of a better quality.

- **Heterogeneity of nodes**: Motes can be different in a network and measure different values. That improves the feature of scalability in the system and allows diversity. On the other hand the maintenance or update of motes will be more difficult.

- **Unattended operation**: Wireless Sensor Networks are characterized as self-organized networks which can be deployed in any environment and work without control of human beings, monitoring and acting over the environment autonomously and recovering from failures.

2.4.2- Constraints and Weaknesses

- **Energy Consumption**: This is one of the main constraints of the motes. The advantage of being developed everywhere brings the disadvantage of the need of using batteries or another way of energy to power the motes. At the moment motes can use standard AA batteries, with a fixed decreasing curve of energy or litio batteries, which keep the same level of energy constant until it is over, or external ways of energy like new capacitors or solar energy. Research is being doing in this area to improve the life of motes from months to years. Now, a mote with 2 AA batteries has a life of 6 to 12 months, depending on the processing activity and communication rate. Because of that, the applications developed for motes should be oriented to minimize the computing activity and the most important, to limit the number of messages being sent and received (communications consume the most of batteries).

- **Communication Limitations**: Contrary to traditional wired networks, WSN communication is based on radio waves with broadcast transmissions on different frequencies which sometimes are not reliable, for example the ISM spectrum, in which WSN devices must compete against more powerful devices. If it is added that the radio stack in motes uses a CSMA access medium protocol without collision detection and no mechanism of retransmission of corrupt messages (TinyOS features, see Section 2.6 and MICA2 features, see Section 6.2) that makes the communication unreliable. Furthermore, the cost in energy for the communication is much higher than computational costs (see stats for MICA2 in Section 6.2) and the protocols are not yet properly developed to be energy-aware. Besides, the bidireccionality (isotropy) is an important characteristic in wireless communication; depending on the use of the network, it could be interesting guarantee the bidirectional communication between two motes, it is said both motes can send and receive from each other. When motes provide data in a tree-based structure, the data flows in one direction, so bidireccionality is not mandatory but if the motes could connect each other to configure themselves, then bidireccionality would be mandatory. Because of that, this is another main concern of the protocol developed in this dissertation; the protocol guarantees bidirecctionality.

- **No location**: Although ad hoc protocols can discover the topology of the network and manage mobility of motes, sometimes it is useful and necessary to get the exact position of motes at each time. It has been developed algorithms [8] where using triangulation, knowing three static motes, the rest of motes can be localized, but it is not very accurate. GPS technology can be a solution but it will bring expensive overheads.

- **Scale**: Although scalability in this type of networks has many advantages like providing better data quality and fault tolerance, it can bring consequences when the number of motes in the same area increases. Protocols have to be provided with good decision algorithms to choose the routes, trying to balance the network energy-efficiently. Clusters hierarchies can be created and data aggregation used within the clusters. Intermediary nodes can get huge overload.

2.5- Applications

There is diversity and huge number of applications currently being researched but this new technology will offer bigger possibilities. Together with typical applications for traditional sensors, this technology provides those applications that because environment conditions (impossible to wire or power) could not be reached.

Below it will be described some interesting applications and projects currently being developed that Wireless Sensor Networks make possible:

- **Habitat Monitoring**: This is one of the main areas in where Intel Research Berkley Laboratory and the College of the Atlantic are deploying and using wireless sensor networks to study the microhabitats on the island of Great Duck, Maine (North American coast)[9]. This is a project that uses WSN to monitor underground nests of the storm petrel, a type of seabird, which has been very difficult to study and whose preferences of living are mainly based on this island. With this, the scientifics will know why this type of bird prefers this island, if this is associated to the microclimate and all of that without modifying aggressively the habitat of the bird. For this purpose it has been introduce a “mote” into the nests and another one outside, 4-inches far away, to receive sensing data like temperature, from the underground mote. The motes outside communicate each other and send the data retrieved in the motes through the sensor network to a gateway which is connected to a laptop in the research station, then to a satellite and finally to a lab in California (see Figure 2.2). As the biologist Anderson says in [10], this technology will change the biology forever.

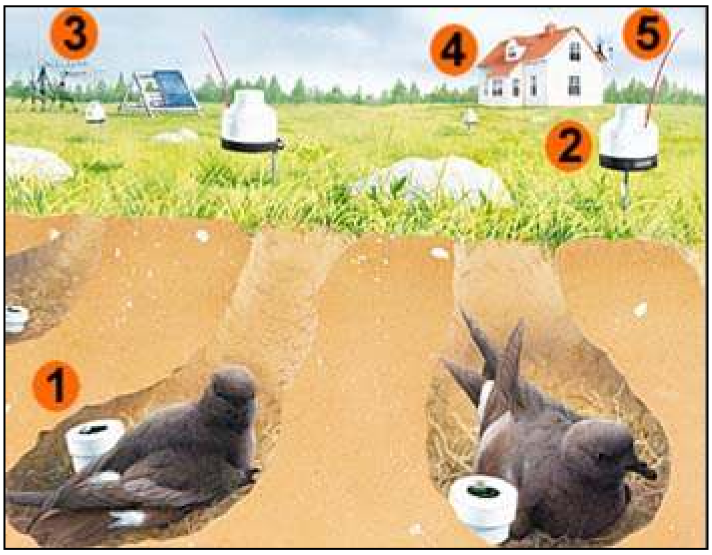


Figure 2.2: Wireless Sensor Network in the Great Duck Island, monitoring the storm petrel (seabird). From 1 to 5 it indicates the process of transmitting data from the motes to the gateway and finally to the satellite [10].

- **Environmental Control**: In the botanic gardens in Huntington, San Marino (California), where there are more than fifteen thousand different species of plants, researches of the Jet Propulsion Laboratory (JPL) of the NASA are currently working with a web Wireless Sensor Network to controls the humidity, hot, ground state, … [11]. Every certain time, the sensors update themselves, sending the information to a gateway that sends the data to the supervisors.

- **Military Surveillance**: As it happened with the creation of Internet, the Defense Advance Research Projects Agency (DARPA) is one of the main research groups trying to develop this technology. In fact the idea of "smart dust" was created by a researcher in this agency; it is based on spreading over the battle field, thousands of sensors which connect wirelessly [12]. These sensors will control the movements of the troops and the enemy vehicles without warning them. The sensors will form an intelligent, auto-organized network which could retrieve all data and just send the important data. DARPA is working in collaboration with the University of California, Berkeley and Intel Company within the Center for Information Technology Research in the Interest of Society (CITRIS).

- **Medical Monitoring**: Intel currently has some lines of research in this field, for example the creation of centers of medical attention to help patients with memory problems and alert them to take its medicaments. Motes can be monitoring vital signs, sending this information through ambulances all over the city, so the closest one will have information about its patients in an action radius.

- **Intelligent Building Control**: In the design of "intelligent" buildings one of the main concerns is the sensors network. Often there is not possibility of installing wired networks in historic buildings, monument and generally after construction; for this purpose WSN can be installed everywhere nearly without modifying the environment. Besides sensors in WSN have a more powerful analysis of the information through the wireless connection so the flow is faster and the decisions can be taken faster. These sensor offers information about temperature, humidity, sound, light, presence control, etc… Moreover, it is being developing GPS indoor systems which allow mobility of sensors to specific positions to control everything even if the sensors are not initially positioned properly.

Other interesting areas of applicability are: Security, Inventory Tracking, Smart Spaces or Traffic Control, but the possibilities are huge.

2.6 – NesC and TinyOS

2.6.1- NesC

NesC is a new structured, component-based programming language for networked embedded systems like Wireless Sensor Networks. NesC has a C-like syntax (extension to C) designed to embody the structuring concepts and execution model of TinyOS, the operating system for WSN.

According to [13], these are the basis of NesC:

- **Separation of construction and composition**: Programs are built out of components, which are assembled ("wired") to form whole programs. Components define two scopes, one for their specification (containing the names of their interface instances) and one for their implementation.

- **Specification of component behaviour in terms of set of interfaces**: Interfaces may be provided or used by the component. The provided interfaces are intended to represent the functionality that the component provides to its user; the used interfaces represent the functionality the component needs to perform its job.

- **Interfaces are bidirectional**: Interfaces specify a set of functions to be implemented by the interface's provider component (*commands*) and a set to be implemented by the interface's user component (*events*). Interfaces allow communication between components in the way of a *command* executing an action that goes downwards through the components in layers and *events* coming upwards in the hierarchy of layers (as a result of a command or an interruption). For example when a packet is sent with the "send command" from the SendMsg interface, an event "sendDone" (which must be implemented in the user component) will be signalled if it has been successfully sent. This allows a single interface to represent a complex interaction between components.

- **Components are statically linked to each other via their interfaces**: This increases runtime efficiency, encourages robust design, and allows for better static analysis of programs.

- **NesC is designed under the expectation that code will be generated by whole-program compilers**: Everything will be compiled statically so there will no be problems like dynamic memory allocation and data race conditions can be detected (nesC owns a detector). This allows for better code generation and analysis.

- **The concurrency model of nesC:** Is based on run-to-completion tasks, interrupt handlers which may interrupt tasks and each other and detection of data races at compile time. Components have internal concurrency in the form of tasks. Threads of control may pass into a component through its interfaces. These threads are rooted either in a task or a hardware interrupt.

- **Files for NesC have the extension ".ns" for all type of components.**

According to [14] those are the challenges that have to be addressed in this type of embedded systems (WSN):

- **Driven by interaction with environment:** WSN are specific-purpose rather than general-purpose computing systems, event-driven (reacting to changes in the environment) rather than driven by interactive or batch processing. Consequently, events and processing activities need a concurrency model.

- **Limited resources:** It considers that motes have very limited physical resources, because of its characteristics so it has to minimize the use of those resources doing it efficiently.

- **Reliability:** It is expected that these systems runs with autonomy for long, and since there is no real recovery mechanism and fails in hardware can be expected, reliability has to be guaranteed in the software level.

- **Soft real-time requirements:** These type of systems (WSN), although they can require time critical tasks (radio management or sensor polling), they do not really need hard real-time guarantees. Timing constraints can be addressed by having control over the OS and application.

Based on challenges above and after combining properties of different programming languages, these are the global features of NesC [14]:

- NesC integrates reactivity to the environment, concurrency and communication. As it is oriented to this type of concurrent systems where resources are limited, it performs whole-program optimizations and compile-time data race detections to simplify application development, reduce code size and avoid potential bugs, in order to maximize the efficiency.

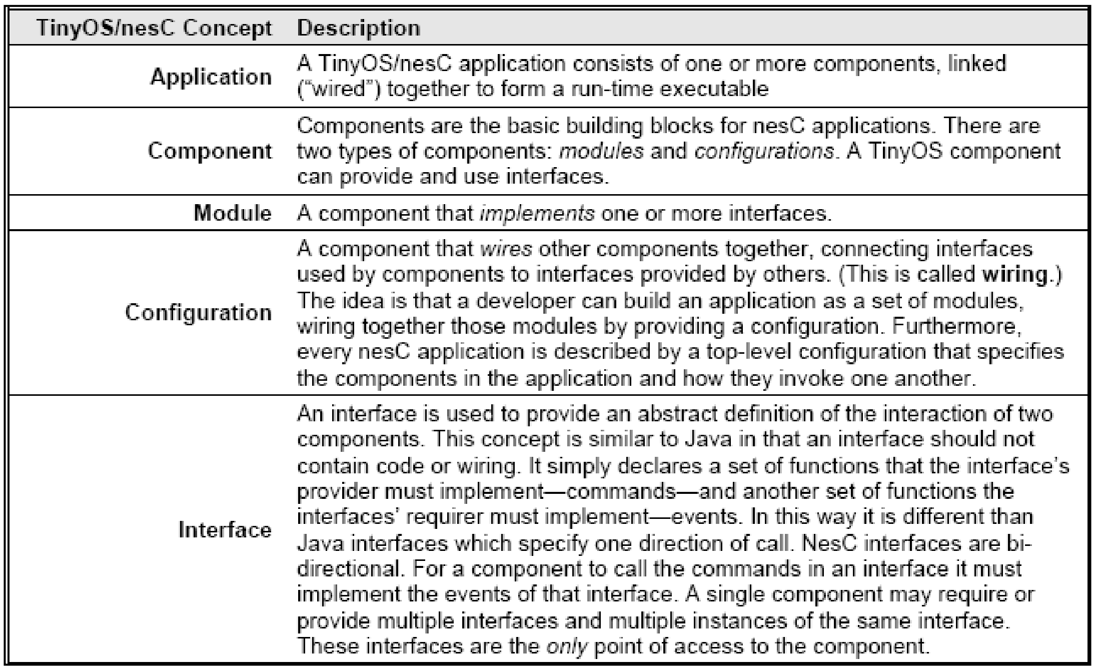
- Because of the fact that nesC is oriented to systems which are hardly tied to hardware, all resources are known statically and applications are built from reusable component libraries. Besides nesC compiler performs static component instantiation, whole-program inlining, and dead-code elimination.

- Although function pointers and dynamic memory allocation were prohibited nesC is capable of supporting complex applications.

- The design of applications has to be flexible, to easily decompose it and be able to integrate in different hardware platforms where the boundaries between hardware/software can vary. NesC provides bidirectional interfaces to simplify event flow, supports a flexible hardware/software boundary, and admits efficient implementation that avoids virtual functions and dynamic component creation.

- NesC defines a simple but expressive concurrency model coupled with extensive compile time analysis: the nesC compiler detects most data races at compile time.

- NesC provides a balance between accurate program analysis to improve reliability and reduce code size, and expressive power for building real applications.



TinyOS/nesC Concept	Description
Application	A TinyOS/nesC application consists of one or more components, linked ("wired") together to form a run-time executable
Component	Components are the basic building blocks for nesC applications. There are two types of components: *modules* and *configurations*. A TinyOS component can provide and use interfaces.
Module	A component that *implements* one or more interfaces.
Configuration	A component that *wires* other components together, connecting interfaces used by components to interfaces provided by others. (This is called **wiring**.) The idea is that a developer can build an application as a set of modules, wiring together those modules by providing a configuration. Furthermore, every nesC application is described by a top-level configuration that specifies the components in the application and how they invoke one another.
Interface	An interface is used to provide an abstract definition of the interaction of two components. This concept is similar to Java in that an interface should not contain code or wiring. It simply declares a set of functions that the interface's provider must implement—commands—and another set of functions the interfaces' requirer must implement—events. In this way it is different than Java interfaces which specify one direction of call. NesC interfaces are bi-directional. For a component to call the commands in an interface it must implement the events of that interface. A single component may require or provide multiple interfaces and multiple instances of the same interface. These interfaces are the *only* point of access to the component.

Table 2.2: Description of the main TinyOS/nesC components [13]

2.6.2- TinyOS

According to [15], tinyOS is an open-source, component-based, event-driven operating system designed for wireless embedded sensor networks in which devices have very limited resources. It has a very small footprint, the core OS requires 400 bytes of code and data memory combined [16]. Actually nesC was designed to support and evolve TinyOS's programming model and to re-implement TinyOS in the new language. In fact, nesC was created to suit the needs of TinyOS, so principles are the same in both nesC and TinyOS.

TinyOS has several important features that influenced nesC's design [14]:

- **Component-based architecture:** TinyOS features a component-based architecture, which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. It provides a set of reusable system components in libraries which includes network protocols, distributed services, sensor drivers, and data acquisition tools. Components are organized according to functionality and it is followed a layer architecture (see Figure 2.3). An application connects components using a wiring specification that is independent of component implementations. Components can be modules (implement the behaviour) or configurations (link -wire- components) (see Table 2.2). Decomposing different OS services into separate components allows unused services to be excluded from the application.

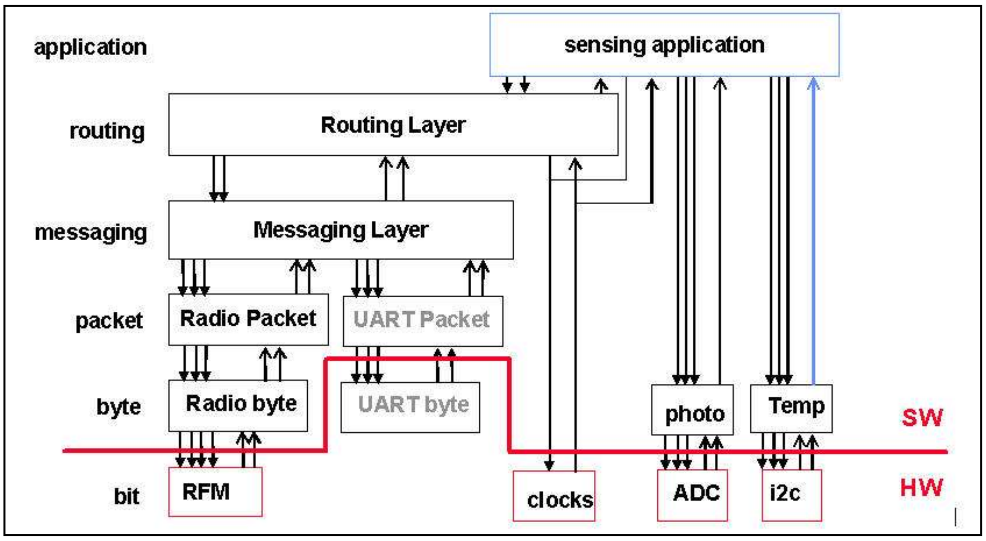


Figure 2.3: TinyOS component layer architecture [16]

- **Tasks and event-based concurrency:** There are two sources of concurrency in TinyOS: *tasks* and *events*.
    - *Tasks* are a deferred computation mechanism. They run to completion and do not pre-empt each other. Components can *post* tasks; the post operation immediately returns, deferring the

computation until the scheduler executes the task later. Components can use tasks when timing requirements are not strict; this includes nearly all operations except low-level communication. To ensure low task execution latency, individual tasks must be short; lengthy operations should be spread across multiple tasks. The lifetime requirements of sensor networks prohibit heavy computation, keeping the system reactive.

    - *Events* also run to completion, but may pre-empt the execution of a task or another event. Events signify either completion of a split-phase operation (discussed below) or an event from the environment (e.g. message reception or time passing). TinyOS execution is ultimately driven by events representing hardware interrupts.

Commands and events that are executed as part of a hardware event handler must be declared with the *async* keyword.

Because tasks and hardware event handlers may be preempted by other asynchronous code, nesC programs are susceptible to certain race conditions.

Races are avoided either by accessing shared data exclusively within tasks, or by having all accesses within *atomic* statements.

The nesC compiler reports potential *data races* to the programmer at compile-time. It is possible the compiler may report a false positive. In this case a variable can be declared with the *norace* keyword.

The simple concurrency model of TinyOS allows high concurrency with low overhead, in contrast to a thread-based concurrency model in which thread stacks consume precious memory while blocking on a contended service. However, as in any concurrent system, concurrency and non-determinism can be the source of complex bugs, including deadlock and data races.

- **Split-phase operations:** As was described for nesC, commands and events perform operations by splitting responsabilities. Tasks execute non-pre-emptively so TinyOS has no blocking operations, then the only way to address it is split long-latency operations. “Commands” are typically requests to execute an operation; if the operation is split-phase, the command returns immediately and completion will be signalled with an event. An example is the sending process, a command request the sending of a message and if it is successful and event is signalled.

Non-split-phase operations like toggle an LED do not have completion events.

Resource contention is typically handled through explicit rejection of concurrent requests.

Chapter 3 – Ad hoc Routing Protocols

3.1- Introduction

At the time of designing routing protocols, the environment of the application is one of the main important issues to take in mind. The constraints of the technology must be addressed in a way or another to try to minimize them. Besides, the topology will be determined by the routing protocol being used.

In Wireless Sensor Networks where the devices may have mobility, topologies can change dynamically, so the routing process have to be the most efficient possible, based on the principles of an ad hoc protocol (if the devices are static, should not be mandatory), and trying to address constraints like power consumption.

Many routing protocols have been proposed, not only for ad hoc networks but also for wired static and traditional networks. All of them address different constraints, depending on the characteristics of the network to which are applied.

In this chapter it will be explained some of the specifications and workings of some important routing algorithms which have helped in the process of designing the proposed project algorithm.

3.2- Graph based routing

3.2.1- Bellman-Ford

This is one of the most famous used in wired networks. It was used in ARPANET, and it is based on getting the shortest path through a node. The time is the estimation process.

According [17], every router maintains a table with the best distances to reach every node and the paths to achieve it. The tables are interchanged between neighbours to update themselves. For every entry (unique for every destination) in the table, it is saved the preferred exit and an estimation of the time to reach the destiny node.

Any router have to measure distances with its neighbours depending on the type of measure being used (eco packets for delay measure).

Every certain period of time the routers interchange its tables with the neighbours, and with the new tables obtained the router calculates better distances and updates its table if it finds better routes.

3.2.2- Dijkstra

Edsger Wybe Dijkstra created this algorithm in 1959. This algorithm is used in finding the shortest path between a node and the rest of the nodes in the network in TCP/IP networks. Conforming with [17] the estimation is based on a function of weights. The algorithm has a complexity equal to O (n^2) with "n" number of nodes. This is the way of working.

- In a graph, every arc between two nodes will have an associated weight.
- The shortest path to go from a node to another is when the sum of all the weights of the arcs which form the path is the lowest possible from all the available paths between the two nodes.
- It is based on the optimality principle that states: if in the shortest path between two nodes u and v, there is a node w, the path between w and v must be the shortest.
- It uses the already established shortest paths to create other paths, so it takes profit of the information available in the network.

3.2.3- Min-Hop Algorithm

This is based on the Dijkstra algorithm above. It is based on choosing for the next hop on the routing process the node which has the less weight. Because of that it is probably that it is not chosen an optimum path than with the other algorithms. The problem with this algorithm is the overload of the best links (minimum weight) and do not take into account the rest nodes for having less quality, that makes a non efficient and well balanced use of the resources in the network.

3.3- Ad Hoc Routing Protocols

The main feature of this type of networks is its dynamicity; all the nodes have mobility and can leave and enter in new networks at any time so the algorithms should manage all of that possible failures (fault tolerance).

Another concern that this algorithms should address is the efficient use of the energy because usually all mobile devices carry its own power system which have a period or life and mostly the sensors (motes).

Now it will be presented two types of classifications for these types of algorithms:

3.3.1- Routing classification 1

A general classification for routing protocols is based on the time when the routes are discovered, statically or on demand [18]:

- **Pro-active (Table-Driven Routing)**

  This type of protocol works out routes in the background independent of traffic demands. Ever node stores information about the topology of the network in tables, which are updated every time a new message is received. There is a process in charged of sending, receiving and analyzing packets to discover the topology. This information in the tables is then queried to obtain routes to send data to a node. It is slow to converge and may be prone to routing loops. It keeps a constant overview of the topology which creates overhead if there is no data to be sent. This type of algorithm needs resources like power, link bandwidth and storage capacity so depending on the features of the network it could not be suitable for ad hoc routing and neither for Wireless Sensor Networks.

  Examples of this type of routing algorithms are: FSR, DSDV, WRP, CGSR, and STAR.

- **Reactive (On Demand Routing)**

  This type of protocol reacts depending on the need of data being sent. There is no information in tables on how to reach nodes in the topology. When a node wants to send data, it ask tables which store already searched routes, if there is no information on how to reach this node, it starts a discovery process. The discovery process uses different methods to obtain different paths, the most well known is flooding. Once it is obtained the best route it is saved in the table of the mote to avoid repeating the discovery process again (out of date routes are controlled with timestamps). This type of algorithm is very efficient for ad hoc networks when the route discovery is less frequent than the data transfer. They are more suited to large networks with light traffic and low mobility.

Examples of algorithms are: DSR, ABR, TORA, AODV, CBRP, and RDMAR

- **Hybrid (Pro-active/Reactive)**

It is combined both pro-active and reactive protocols using distance-vectors for more accurate metrics to establish the best paths and it react reporting routing information just when there is a change in the topology of the network. Each node in the network owns an action radius zone, defined by metrics like number of hops; the node just keeps information in tables about its zone, minimizing the content in the tables.

The most well known example is Zone Routing Protocol (ZRP).

3.3.2- Routing classification 2

Classification according to the way the neighbours are searched and the paths are found:

- **Flooding**

A message from a node is sent to all its neighbours and those to its neighbours too and so on, sending copies of the message to all the nodes in the network, The problem is the collisions mainly in wide networks, it has to be checked to avoid cycles (do not send the same message to your neighbours twice). Besides there is a waste of energy in sending all these messages all through the network but depending on the use of the message data to update every node, it can be taken profit from the process.

- **Bellman-Ford Algorithm**

Although it was described in section 3.2.1 as a non ad hoc algorithm, it can be applied to ad hoc networks too. The difference will be that all nodes keep routing tables then all nodes will act as routers. The problem with this algorithm comes when the networks are too wide, the tables need a lot of entries to be fault tolerant and the memory in mobility nodes is an important constraint.

- **Gradient Algorithm**

According to [19], it is a kind of flooding because the messages are not sent to a specific node; they are sent to their neighbours. In this algorithm tables with weights are defined which give information or measure about what route should be followed. The tables are not transferred through the network. Although the message is sent to all the networks (act as a routing), each node which receive a message and will decide consequently so the number of messages being sent will not increase that much as in flooding (see above).

- **Stigmergy Algorithms (Ant Algorithm)**

Based on that [20], this type of algorithms tries to imitate the behaviour of some colonies-life animals when they have to discover paths to get the best way through the food, and how they follow each other based on probability and the modification of the environment. For example in the case of ants, they discover the optimum path to the food by leaving pheromones in the way. As the shortest route will contain more concentration of pheromones (more ants will cross the shortest way faster), all the ants will end up following the most "smelly" path. At the beginning of the process they apply functions of probability and pheromone concentration but once the pheromone concentrations starts to get bigger, the pheromone measure becomes the main estimator to follow the route.

3.3.3- OLSR (Optimization Link State Routing) Algorithm

This is a proactive routing protocol, using flooding technique to determine the topology in the network. The information containing the topology is sent to all the nodes using flooding which provides available routes quite fast without a huge overload. The protocol should be independent from the layers above (data-link layers), that's why it is based on how to communicate or features of the communication as estimation of the quality of the link.

These are the three mechanism used in the protocol [21]:

- **Neighbours Discovery Mechanism**

The link between a node and a neighbour can have these three states:

- No link: There is no communication with the neighbour.
- Symmetric: The communication from the node to the neighbours exists as well as from the neighbour to the node.
- Asymmetric: The communication just flow in one direction, from the neighbour to the node or vice-versa.

To detect neighbours a node transmit periodically HELLO messages, with information like the address of the node, the list of neighbours and the link state with them, in order to detect changes in the network.

With this, a node which receives the messages can determine the state of its neighbourhood as well as the nodes which are 2 hops far it. This information is stored in each node and has to be saved for a certain time and updated with the next HELLO messages.

- **Traffic Control Mechanism**

With the information of the link state from the neighbours and the nodes 2-hop far, now it has to be controlled the data flow with which the network will be flood to discover the topology. This is based in a simple mechanism based on flooding.

To control the network it is used a flooding control message. When a node receives this message for the first time, it forwards it to its neighbours. Doing that neighbours will get duplicate messages but it is ensured that the message will be received by all nodes.

Collisions will be a problem with the messages from the nearest nodes so the algorithm defines the Multipoint Relay (MPR), which are nodes selected to send the messages to the node 2-hop far away. These nodes must have symmetric link with the source node. The way of selecting this type of nodes depends on how they will be used, taking into account the minimum number of nodes needed to retransmit a message 2 hop distance.

To control the flooding process of these messages, these rules have to be followed:

- The message should have the intention of being forwarded.
- The message must not have been received by the node previously.
- The message received must come from a node selected as a MPR.

- **Routing Mechanism**

In order to route the data over the network every node has to get the information about all nodes in the network. To do that it is used the Topology Control (TC) messages, which contain the source address and the address from the MPR's. These messages are sent by the nodes which own a MPR. The purpose of these messages is to advertise what connectivity has the MPR, so the nodes will receive a graph with partial information about the network topology. This information is enough to apply an algorithm to select the shortest path. This information will be valid for a period of time until it is updated.

3.3.4- Direct Diffusion Algorithm

It is based on data-centric routing and it is very lean to sensor networks. The purpose of the algorithm [22] is the diffusion of data through sensor nodes by using a naming schema for the data, in order to avoid unnecessary operations of network layer routing to save energy.

It uses attribute-value pairs for data and the sink queries the sensors in an on demand basis. To create a query an interest is defined using a list of attribute-value pairs such name of objects, interval, duration, geographical area, etc. The interest is broadcasted by the sink to all of the nodes in the network which stores the interests to compare them later with the data received and decide where to route. The interest entry also contains gradient fields and it is used both of them to create the paths between sink and sources. The gradients are very useful to determine quality of paths, as they are reply links to neighbours, from which the interest came from, containing data rate, duration and expiration time.

As many paths can be established in the process, the path is selected by reinforcement with the sink resending the original interest through the path with a small interval forcing the source node to send data more frequently. A very interesting feature of Direct Diffusion is the re-identification of a new route among the other possible paths in the event of an already established path fails, by reinitiating the reinforcement process. Multiple selected paths can be previously selected to save energy cost in the process of reinforcement but there will be extra overheads of keeping those paths.

There is no need for addressing mechanism as it is data centric with communication neighbour to neighbour, each node can aggregate data and there is no need to maintain global network topology.

Because of the fact that the algorithm is based on a query-driven on demand model, applications which require continuing monitoring from sensors to the sink will not work efficiently.

3.3.5- Rumor-based Algorithm

The idea of this type of routing is the use of “agents”, to create the paths through the network to the events when they happen [23]. Agents are messages with expiring time which travel over the network. After the agents generate these paths the “queries” are routed following them. Firstly the queries are sent by a random path. Each node in the network keeps a neighbour table and another table for events that contain the information of the expeditions which have gone through it. At the beginning, lists of neighbours are generated broadcasting each node’s identification. When the events have a limited life time, timestamps can be used in the events tables.

3.3.5.1- Agents (path creators)

The paths are stored as states in the nodes and are created by the agents. The agents are created in the nodes of the event adding a path of length 0 to the event. The agent is generated in a probabilistic way to avoid overhead when many nodes generate the same event and many paths go to the same event.

The agent travels over the network for a maximum number of hops. It carries its own event table which combines with the event tables of the nodes it visits.

When an agent cross a path which goes to another event, the agent start to create paths to both events (see Figure 3.2).

When an agent finds a node with a longer path to the event, it updates the node routing table with the shortest path (see Figure3.1).

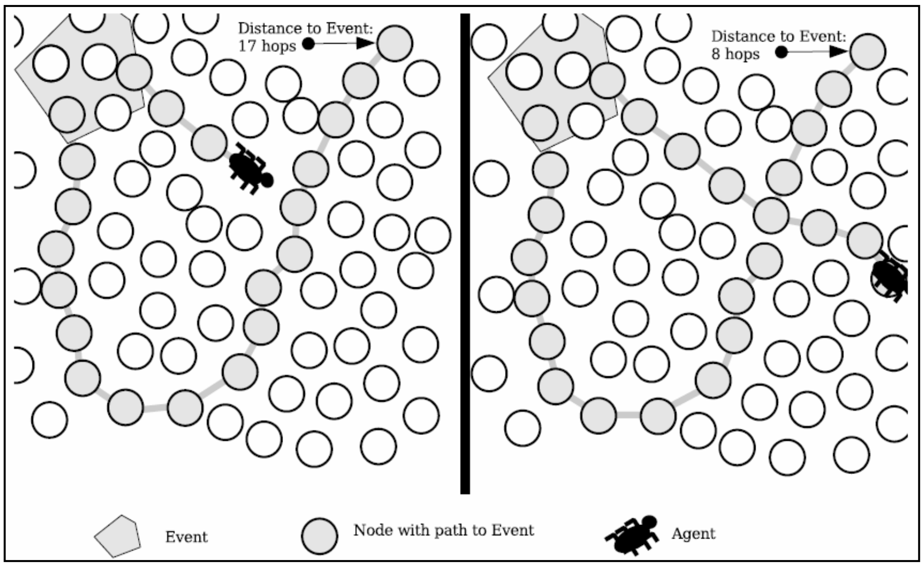


Figure 3.1: The agent modifies the exist path to a more optimal one [23]

The agent uses an algorithm to correct the path in order to generate better paths by registering the nodes recently visited (avoid cycles) and communicating with its neighbours in each node.

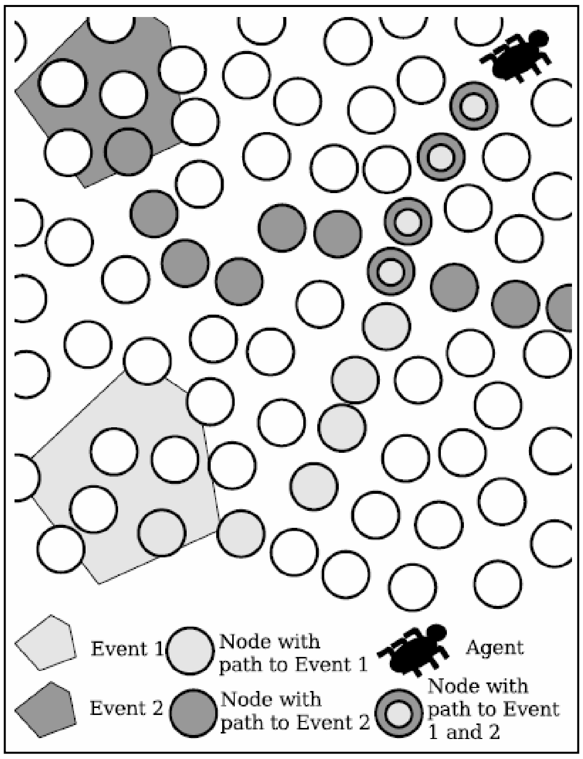

Event 1
Node with path to Event 1
Agent
Event 2
Node with path to Event 2
Node with path to Event 1 and 2

Figure 3.2: When agent prorogation the path to Event 2 comes across a path to Event 1, it begins to propagate the aggregate path to both [23]

3.3.5.2- Query Routing

Query messages firstly travel in a random direction until they find a path, which brings them to the node they ask for or they just stop because the maximum hop has been reached (see Figure 3.3). When the query is sent randomly, it is used the algorithm that the agent uses to correct the path. If the destiny is not reached by the query message, the node which generates the query can retransmit it again or flood the network with the query.

Loops are produced and must be detected by hop count or storing recent query's identifications. If the node receives a repeated query, it is not sent by the path; instead it can choose a random path.

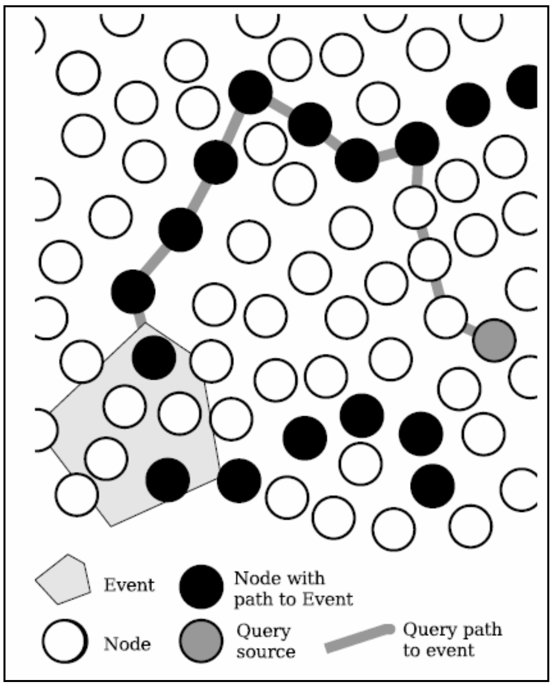


Figure 3.3: Query is originated from the query source and searches for a path to the event. As soon as it finds a node on the path, it's routed directly to the event [23]

3.4- Link State Estimation

There are many different systems to estimate the link state, systems which performs great in wired networks and which can not be used in wireless because of the complete different principles in communication between nodes. Wireless systems are driven by failures in communication; the transmission mean is less reliable so the metrics for evaluation which includes agility, stability and amount of history required for estimator, have to be well tuned according to the constraints of the wireless network.

For the purposes of Wireless Sensor Networks, it has been evaluated several estimators as in [24]; the most significant and successful will be described in this section.

3.4.1- EWMA (Exponentially Weighted Moving Average)

This estimator is very simple, widely used and memory efficient but it requires constant storage for history tuning.

It is reactive to small shifts, often used in statistical process control applications detection because of its agility. It is based on a linear combination of infinite history, weighted exponentially, updating the history with packets received successfully according to a time interval which is suppose to be the time in between the reception of two consecutive packets; with the time interval, which has to be tuned, it can be calculated how many packets were lost and make the calculations for the estimation.

The implementation of EWMA will take 4 bytes (floating point) or 1 byte (fixed point) to store the current estimation with just 2 multiplications and 1 addition involved in the computational process.

The process of tuning [24] indicates that in order to keep the estimation within a 10% error, the agility has to be sacrificed. On the other hand if it is tuned to provides agility, good for detecting disappearance of neighbour nodes over a relatively short time, the estimation will not be very useful because of the large overshoots and undershoots (sensitive to small shifts). Besides, it was measured that the crossing time for EWMA is 167 packets while settling time is close to 180 packets.

3.4.2- Flip-Flop EWMA

As it was described above, it is quite difficult to provide both agility and stability in the same estimator, because of that it is proposed a flip-flop between two EWMA estimators which implement stability and agility features.

In [24], this approach was tested; the switching between agile and stable estimators was produced when the difference in deviation was greater than 10%. On the other hand if the estimator by default was stability, it changes to the agile estimator when it can be detected sudden changes such as mobility much earlier. It was shown in [19, 24] that the flip-flop does not provide advantage over EWMA, but it could be caused because of the switching threshold.

3.4.3- WMEWMA (Windows Mean EWMA)

It uses the average of a time window to adjust the estimation using the latest average which is actually an observation of the estimation. EWMA then is applied to filter more the estimation. It is based on messages received and sum of losses to calculate a mean in which is involved 2 additions, 1 division and two multiplications as computational operations, saving the result in 1 byte (fixed point) or 4 bytes (floating point), same as in EWMA, but with the different of using 2 bytes to store the number of messages received and looses. The computation is done in function of the time window instead of every certain time event.

According to [24], the observed settling time and crossing time is relatively small, the fastest of all studied but as EWMA is sensitive in the agile scenario there is not significant improvement.

Chapter 4: Routing in TinyOS

4.1- Introduction

The process of routing in Wireless Sensor Networks is based on that of ad hoc routing protocols which can support the mobility of motes (nodes). The nature and novelty of WSNs, together with the difficulty of debugging make direct implementation extremely challenging [25]; therefore most of the current ad hoc algorithms have only been tested in simulators, but not on real motes.

The main objective in routing is to carry information from the motes to the root mote or base mote, which is then connected through a gateway to a computer which can analyze, transform or publish the data.

The main objective in ad hoc routing protocol design is to have the motes acting as data retrieval devices, directing this information through a root mote for late data analysis. Two topologies have been used to classify the networks and hence in the design of new ad hoc protocols; these topologies are: tree-based and cluster-based. Because of the nature of the monitoring process WSNs fit perfectly into these systems and hence allow the designers of new ad hoc algorithms to address constraints such as minimizing the number of communication messages being sent, leading to a reduction in power consumption by the motes.

In this chapter the routing process in TinyOS will be detailed. As discussed previously many different versions of TinyOS exist; in this chapter the routing system used in all versions within 1.x. will be detailed. This type of routing is based on a hierarchal topology like the tree-based topology.

Overview of the new algorithms provided with more recent releases of TinyOS, v2.0. will be described. Two new ad hoc routing algorithms have been produced: one of them is based on data aggregation while the other is concerned about dissemination of routing data over the network. Hence although the hierarchy is maintained, both routing directions can be taken, i.e. to and from the root mote.

4.2- Architecture of the Ad hoc Routing Component

After studying many routing algorithms with different inherent problems, Philip Levis, one of the creators of TinyOS, created the first architecture to provide multihop routing in WSN [26]. One issue that theses addressed was separating policies from mechanisms; in that the architecture was capable of incorporating different algorithmic building blocks, each of which can be easily interchanged.

The data movement and route decision engines were split into separate components with a single interface between them. This permits other route-decision schemes to be easily integrated and evaluated.

The architecture created and the components of the routing protocol can be seen in Figure 4.1. At the upper layer is the application component. Between this application layer and the multi-hop component are an arbitrary number of network stack components which are represented by the transport layer. An application interacts with the network stack through the Send and Receive interfaces; use of the Intercept interface is optional however it is frequently used to sniff packets.

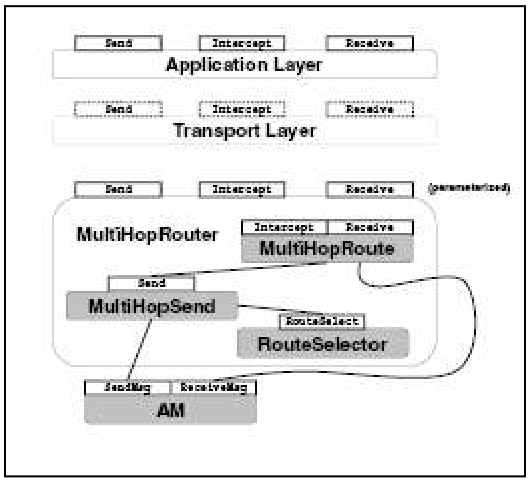


Figure 4.1: Component Architecture [26]

The TinyOS-1.1 release and later releases include library components that provide ad-hoc multi-hop routing for sensor network applications [27]. The implementation uses a shortest-path-first algorithm with a single destination node (the root) alongside active two-way link estimation.

4.3- EWMA Multi Hop Router Algorithm (the 1st one)

This was the first algorithm implemented with a component architecture as in Figure 4.1. It uses an exponentially weighted moving average (EWMA) for link estimation [24].

As for all the applications written for TinyOS it uses a configuration file to connect (wire) the components and establish which interfaces are provided and used, as well as the modules of the new application. The structure of the components is as follows:

- MultiHopRouter (configuration) - is the top-level configuration for the routing layer, which wires (connects) the next modules.
- MultiHopSend (module) - is responsible for sending packets using the implemented ad-hoc routing protocol. It is responsible for decisions like when and how many times to retransmit and when alternate parents should be requested. When a new message needs to be sent it calls the RouteSelector component interfaces to prepare the package.
- MultiHopRoute (module) - is responsible for receiving protocol messages and deciding whether it should forward them. If a message has to be forwarded then it passes the packet to MultiHopSend which will call RouteSelector to prepare the packet.
- RouteSelector (module) - is the component that can be easily interchanged. It maintains routing state, which it uses to choose routes for packets to send. MultiHopSend passes it a packet buffer, which it fills in with the necessary header fields to be used by MultiHopRoute. This is the component that makes the decisions of routing based on estimators (e.g. Link Quality Estimator, Geographic Position Estimator, and Power Estimator).

The nodes keep a table of neighbour in order to keep track of the neighbours which are accessible within one radio hop. The information in the table is based on the information received from other nodes. Information about the parent (node through which it arrives to the root) is stored and is based on ack/nacks that the parent sends.

The estimation technique in EWMA is based on the link state; a better description can be found in Chapter 3.

The success in receiving packets is calculated by the difference in the sequence number, so the reception of messages has to be an small multiple of the time interval, otherwise the failure is based on an accumulation of a silent count where there is no reception.

The ack received from the parent is used to increase the value of this node as the parent, in comparison with the rest of the neighbors.

4.4- WMEWMA Multi Hop Router Algorithm (the 2nd one)

The second version of the algorithm follows the same architecture of that outlined above, for version 1.x of TinyOS. The difference with respect to its predecessor is that the link estimator measure is based on WMEWMA (Window Mean with EWMA) which offers more efficiency and simplicity [28].

According to [27], the configuration which wires (connects) the new components is given in Figure 4.2; the direction of arrows indicates interface provider/user relationships, not data flow direction.

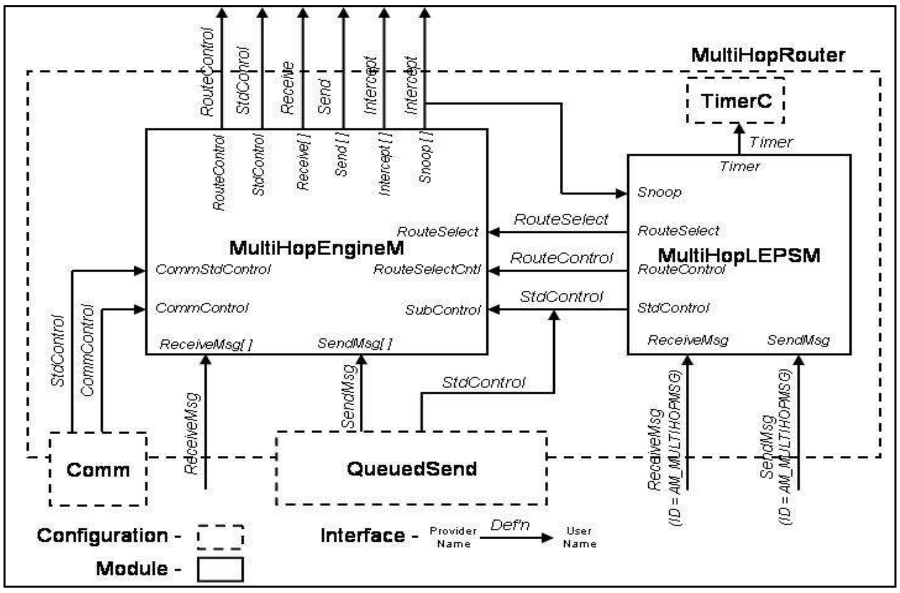


Figure 4.2: MultiHopRouter configuration [27]

Applications should maintain an average message frequency at or below one message every 2 seconds. Higher rates can lead to congestion and or overflow of the communication queue.

4.4.1- Interface Description

The component configuration provides 6 interfaces. A '[ ]' after the interface name indicates the interface is parameterized and it can contains any type of AM messages defined in an ".h" file.

- StdControl - The standard control interface
- RouteControl - A special interface for controlling monitoring router - operation. This is the interface called to obtain the route to the parent.
- Receive[] - In this implementation, the base station is the only implicit destination for packets, as it is the sink in the topology. This interface exists only as a stub and is not implemented.
- Send[] - The port to use for locally originated packets.
- Intercept[] - This port is used when a packet is received that will be forwarded. It provides a means for an application to examine forwarded traffic and, depending on the value returned, suppress the forwarding operation in order to control cycles.
- Snoop[] - The Snoop port uses the 'Intercept' interface definition, but with different semantics. It is signaled when a packet is received that will not be forwarded. This interface is useful for passive monitoring of traffic for replication purposes.

4.4.2- Component Description

The components have changed relative to the previous version but the architecture schema has been maintained. The configuration file is the same but has internal code to multiplex between the two versions (different names and new interfaces). These are the configuration file and the modules:

- MultiHopRouter - This configuration connects MultiHopEngineM, MultiHopLEPSM with other necessary components (queueSend, comm, timer…) which are more primitive components used to access the low layers in the architecture. These are the main tasks of this configuration file:

  - Exports the Receive, Send, Intercept and Snoop ports to applications.
  - SendMsg port of MultiHopEngineM is wired (connected) to the QueuedSend library components for queuing outbound packets (both forwarded and locally originated).
  - ReceiveMsg and SendMsg ports of MultiHopLEPSM are wired (connected) to the AM_MULTIHOPMSG parameter of the communication provider for the purpose of exchanging single-hop route updates with neighbors.

- MultiHopEngineM - Provides the overall packet movement logic for multi-hop functionality. It only requires that the RouteSelect and RouteControl interfaces be available.
  - Using the RouteSelect interface, it determines the next-hop path and forwards the packets out the parameterized SendMsg port.
- MultiHopLEPSM - Provides the Link Estimation and Parent Selection (LEPS) mechanisms for the multi-hop implementation.
  - It monitors all traffic received at the node via the Snoop port.
  - It directly receives single-hop route update messages (AM_MULTIHOPMSG) that may be sent from neighbors within the single hop range.
  - The module internally sends and receives AM_MULTIHOPMSG messages to manage the nearest available neighbors and it decides the next hop destination based on shortest path semantics.
  - The root node (address=0) or sink is discovered based on the minimum number of forwarding messages.
  - By default, the module sends a route update message once every 20 seconds and re-computes after 50 seconds (5 route update messages).

- The flexibility in this module is so high that it can be replaced for another one, just following the same convention names and parameters within the interfaces. Thus new estimation measures can be inserted into the routing layer for evaluating. For example, a min-hop algorithm might have an estimator that listens for protocol messages and updates routing tables accordingly.

4.5- Structure of the multihop message

In this section we describe the structure of the message that implements the routing logic of the protocol (see Figure 4.3). All messages must be parameterised by an uint8_t id which identifies the type of messages the interfaces are handling, in this case the id number is 250. As this message will be encapsulated in the data field of a standard sending message TOS_Msg (see Figure 4.4), it has the same length of the data field, 29 bytes. 2 bytes are used for keeping the source address of the sending message, another 2 bytes are used to store the original address of the data being sent, another 2 bytes are used for the control sequence field and a last control field contains 1 byte and is used to store the number of hops the packet has been carried so far. The type of message being sent by any application must fit into 22 bytes (29-7 bytes). So it can be seen that many different type of messages may be sent in the base message using the structure based on the data field as a nested link. Because of this the interfaces are often parameterized to allow for easy identification of the type of message being sent and to allow the bytes with the appropriate message struct type.

```
enum {
  AM_MULTIHOPMSG = 250
};
typedef struct MultihopMsg {
  uint16_t sourceaddr;
  uint16_t originaddr;
  int16_t seqno;
  uint8_t hopcount;
  uint8_t data[(TOSH_DATA_LENGTH - 7)];
} __attribute__ ((packed)) TOS_MHopMsg;
```

Figure 4.3: AM_MULTIHOP message structure

```
typedef struct TOS_Msg {
  uint16_t addr;
  uint8_t type;
  int8_t group;
  int8_t length;
  int8_t data[TOSH_DATA_LENGTH];
  uint16_t crc;
} TOS_Msg;
```

Figure 4.4: TOS_Msg message structure

4.6- Sending a packet

The use of the multi-hop library component is mostly transparent to the application, in so far as the application uses the Send interface to connect to the mutihop component to achieve multi-hop functionality.

When an application wants to send a packet of a defined type (struct):

- First of all it should call the Send's interface getBuffer command to obtain a pointer to the data region of a mutihop packet, where the data will be nested for transmission. This call allows interface users to remain unaware of the packet format used by the provider. Once the command getBuffer is called, it will automatically initialize the protocol fields to state that the mote is the source for the packet.
- Once the pointer is obtained, interface MultiHopRoute will provide information about routing, e.g. the parent, hops… that can be added to the appropriate field of the message.
- Finally the TOS_Msg buffer, where you get the pointer to the field data within an already nested multihop message, it should be called using the Send interface's send command. This send command is wired (connected) to its equivalent in the MultiHopRoute configuration to provide multihop functionality.

4.7- Receiving a packet

To receive packets from a specified id type in an application, the event Receive.receive, with the parameter [uint8_t] specifying the type of message it is desired to receive, must be declared. The multihop components will then signal the event through to the application layer if the message is from this type and the packet is destined for this mote. Internally the reception of an AM message signals MultiHopRoute which determines if the packet is destined for the local node. If so, it signals MultiHopRouter's Receive interface, otherwise it signals MultiHopRouter's Intercept interface, which will generally forward the packets.

To forward the packet, MultiHopRoute calls Send.send on MultiHopSend, using the same sending policy as if it was the packet originator.

4.8- Other Routing Component Projects

Many other different ad hoc protocols have been developed following the architecture provided. Usually these change the module MultiHopLEPS for a new one with a different estimation technique, e.g. based on power consumption [29], other types of link estimation [30], based on hop count, etc.

A functionality that was not implemented initially in the first routing schema was the aggregation of data. Here, data received from a child mote in the hierarchy is aggregated into a data packet to be sent up through the topology to the root. This technique, explained in detail in [31] produces a considerable reduction in the number of packets being sent, getting more efficiency from the topology and consequently reducing the power consumption.

4.9- New Recently Released Routing Algorithms (TinyOS v2.0)

New protocols have been created to address some of the main constraints or demands in the routing process. These were released in TinyOS version 2.x on July 2006, so they are in beta release and so not completely tested, or not 100% reliable.

All components in both protocols follow the architecture (interfaces, component structure…). The algorithms have different purpose based on the need in WSNs of routing data, and both are ad hoc protocols.

4.9.1- Collection

This is based on the main requirement in WSN of collecting data at the base root as the only sink node for data, using topologies based on trees, sending the data through the nodes to the root. As the nodes will act as routers, they will inspect all the packets received so depending on the purpose of the application it will be able to gather statistics, compute aggregates, or suppress redundant transmissions.

Besides, Collection works with forests of trees: more than one base station can be picked to receive data; every node will pick a parent and implicitly will join one of those base stations.

It is a any-cast protocol; it provides a best-effort, multihop delivery of packets to one of those trees. As it is stated in [32], given the limited state information that nodes can store and a general need for distributed tree building algorithms, simple collection protocols encounter several challenges which represent a subset of common networking algorithmic edge cases that occur in this protocol family:

- Loop detection
- Duplicate suppression (detecting and dealing with when lost acknowledgments)
- Link estimation (evaluating the link quality to single-hop neighbors).
- Self-interference, preventing forwarding packets along the route from introducing interference for subsequent packets.

The new components implementation and logic can be found at its own section at [32]; as it can be seen, the components match the previous version ones but with different functionality.

4.9.2- Dissemination

This protocol has a complete different approach to the routing process than Collection; it is based on the data being routed from the base mote through the rest of the motes. With that it is intended to make the administrators task of reconfigure, query or reprogram easier.

Concerning reliability, this new protocol is much more robust to temporary disconnections or high packet loss; it achieves that by using a continuous approach that can detect when a node is missing the data (that doesn't occur on flooding protocols).

According to the dissemination section et al [32], the dissemination protocol can vary in efficiency depending on the data size being sent; although the control traffic protocol part tends to be the same or similar, the data traffic protocol part depends a lot in the size of data. On the other hand, having a good reliably disseminate protocol based on small values (quite efficient) is enough to cope with the interests of the administrators, taking into account the limited memory resources of TinyOS.

Finally, it has to be commented that this new protocol works with versioning in the event of failure, so the last version it will be the only one seen (although it has been missed some versions with the failure).

The new components implementation and logic can be found at its own section at [32]. It doesn't follow the previous architecture; even the interfaces have not the same logic; now the paradigm is based on producers and consumers of the data.

Chapter 5: Hopping - A bidirectional stigmergy power efficient on-demand driven ad hoc routing protocol

5.1- Constraints to address in Routing on SensorNet

Because of the nature of the motes in SensorNet, there are some issues to keep in mind at the time of designing an ad hoc protocol. Those issues are based on the deficiencies and differences between the wiring powered connected systems and wireless battery dependent ones.

The set of devices, "motes", which communicates via radio (wireless) are limited in memory resources (ROM and RAM) and powered by batteries (AA) which have limited life time (6 months to a year). Besides it has been shown in [33] that the cost in battery of sending a message by a mote is equivalent to calculate thousands of operations.

Having this situation, it has been studied the actual protocol in charged of multihop in SensorNet, for the versions 1.x of the TinyOS as it can be seeing in chapter 4. This protocol works in one direction, sending information from the motes to the base mote, which is the responsible to process the information from each mote. It is based on a tree structure where the root (base mote connected to pc) is the end point and all the rest of the motes use their neighbors to reach it.

Because of that, I believe it will be of great interest and useful application, to create a protocol which communicates among all nodes without hierarchy that even could let a set of motes being independent from the base mote (not connected to any pc), to form self-managed colonies for the purpose of monitoring and controlling .

Furthermore, the reduction of the number of messages being sent among motes it is a goal that will increase the life of the motes. To achieve this goal, and reduce the number of messages generated by the motes (broadcast packets sent every 20 seconds in the actual configuration), it will be changed, in the ad hoc paradigm, from a proactive protocol to a reactive one, where the route will be discovered upon demand.

5.2- The protocol basis

Once studied all the SensorNet architecture, the behavior of the motes, the unidirectional / bidirectional feature in the communication between motes (a mote can reach another mote sending but not be reached by this mote), the type, structure and size of the messages being sent, the memory available in each mote and all different characteristics of the system, this is the proposed algorithm:

- All nodes will have the same status and hierarchy and they will be well defined by an exclusive id mote for each group (example 0x7e).
- All motes will contain a global counter, "sequence message number" and it will be increased with every message sent (not forwarded, except in route discovery).
- There will be two tables for every mote (see Table 5.1 and 5.2).

Reachable Motes	
TargetAddr	**SendMote/SeqRoute**
0x20	0x12/0x125

Table 5.1: Reachable Motes

Routing Table		
RecvMote/SeqRoute	**SendMote/SeqRoute**	**Usage**
0x4/0x23	0x6/0x56	15

Table 5.2: Routing Table

- o *<u>TargetAddr</u>*= Mote address to be reached from this mote.
- o *<u>SendMote/SeqRoute</u>*= Pair "mote address" and "sequence number" which create a unique identifier that indicates that in order to reach the TargetAddr mote, the message has to be delivered to the mote SendMote with this SeqRoute number.
- o *<u>RecvMote/SeqRoute</u>*= Pair "mote address" and "sequence number" which create a unique identifier that the messages, which come from

    the RecvMote with this SeqRoute, have to be sent to the mote SendMote with SeqRoute in order to reach node TargetNode.
    - *Usage*= It is a number that is set to 1 every time a route is created and that is increased every time this route is used; this is the indicator to know which routes are not valid anymore or not used, in order to improve the search process, otherwise the table will grow up with no useful entries.

- An important thing to take into account is that the size of the sequences "seqmsg" and "seqroute" is an int16_t, that will allow a value of 2exp16=0-65535; once a mote reaches this number of messages sent, the solutions would be:
    - It will be sent a flood message to alert all the motes to reset all its counters and start again (start routing process in all motes). All the tables in all the motes will be deleted and the global variable sequence will be set to 0.
    - Another solution will be the update of sequence route numbers with new sequence numbers that will renovate the old sequence numbers guaranteeing that there will be always a distance between the oldest sequence number and the most new number generated avoiding collisions of repeated sequence numbers for a node, even if the counter of the mote is reset to 0. By the time the mote is reset to 0, all the old sequence numbers that form routes will be replaced by far distance numbers within the cycle 0-65536. Those sequence update messages will be generated based on a timer or even better based on the number of message, for example every 500 messages, so it will be guaranteed a minimum distance of 500. The potential problem that has to be measured is that the cost in sending all of these update messages can be higher than the cost of starting the discovery route process again every 65536 messages of the first mote which reach it. Besides sequence numbers in all the tables will have to be updated and if the table gets bigger that could delay the routing.
- It could be thought that routes can change dynamically fast, and better routes can be found, but although that is true, as long as the first route is found and

keeps acknowledging, that will show the route is working and the motes are not moving so much, so the route could not be the best but the difference in time, that will be minimum between routes (because of the action radios), will be coped with the save in number of messages sent to look for a new one.

5.3- Hopping AM message structure

For the purpose of the multihop message, it will be used the structure in Figure 5.1 where the data field will contain the structure of the application message which actually carries the data being sent. Then, the multihop message, which will be called “MHoppingMsg”, will be used to transport the type of message the user is using in the application. The MHoppingMsg will also be nested in the data field of the TOS_Msg structure to be transported. The AM id type to identify the type of message is assigned to id 249 although it could be used the id 250 from the AM_MULTIHOPMSG, because both algorithms are created from the same purpose so it will not produce collisions with any other application layer id’s. As it can be seeing in Figure 5.1, the data field with this type of message will have a capacity of TOSH_DATA_LENGTH(29) – 9, 20 bytes to store any application message that has to be transported.

```
enum {
    AM_HOPPINGMSG = 249
 };

typedef struct HoppingMsg {
    uint16_t targetAddr;    //final destination mote for the msg
    uint16_t senderAddr;    //mote which sends the msg each time
    int16_t seqMsg;         //seq of the message (generated by the origin mote)
    int16_t seqRoute;       //num seq for route of the mote sending
    int8_t type;            //type of msg being sent:
                                -   NEW_ROUTE
                                -   ACK_NEW_ROUTE
                                -   FOLLOW_ROUTE
                                -   ACK_FOLLOW_ROUTE
    uint8_t data[(TOSH_DATA_LENGTH - 9)];    //any type of msg being sent
 } __attribute__ ((packed)) TOS_HoppingMsg;
```

Figure 5.1: AM_HOPPINGMSG message structure

5.4- The procedure, how the protocol works

At any time a mote 0x3 wants to send a message to another one 0x8, it happens this:

- Phase1 (Discover Route): The mote 0x3 doesn't have information about the route in the "Reachable Motes" table (see Table 5.2) to reach 0x8, then:
    - Send a message "TOS_HoppingMsg" (see Figure 5.1) with:

        targetAddr=0x8
        senderAddr=0x3
        seqMsg=value global variable "sequence" for 0x3
        seqRoute=0/null
        type=NEW_ROUTE
        data=none

    - It will be created in the table "Reachable Motes" an entry with the TargetAddr field equal to destination (0x8) and the SeqRoute field with the value of the seqMsg being sent, in order to be able to receive the ack message (there is no information of the source mote in the destination mote).
    - The motes in between will forward the message that will be received by all its neighbors. Those neighbors will forward it flooding the network.
    - When a message is received by a mote with type=NEW_ROUTE that means there is no route established yet and then it will be forwarded to everybody (even if it contains the route for the target node).
    - Every mote in the middle will fill the table "Routing Table" (see Table 5.1) with the received message fields senderAddr (RecvMote) and its seqMsg (SeqRoute), and it will associate the pair with the other pair SendMote (its own address) and SeqMsg (its current sequence number), pair that will be sent in a message.

- All the motes which receive it will do the same except for the target one, checking if the RecvMote and SeqMsg, in the table "Routing Table", of the message received already exists; that means the message is turning into cycles (consequently no forward the message again) because of the fact of flooding the network.

- When the target mote receives the message, it will identify by the field "targetAddr" that it is for it, then it will send an ack message "TOS_HoppingMsg" like this:

  targetAddr=null (no info)
  senderAddr=0x8
  seqMsg=value global variable "sequence" for 0x8
  seqRoute=ReceiveMote/SeqMsgReceived
  type=ACK_NEW_ROUTE
  data=none

- Now the field "seqRoute" is filled with the RecvMote and the SeqMsg (received) and sent to the mote RecvMote. Once the mote receives this message it will search in its Routing Table for SendMote/SeqMsg = RecvMote/SeqMsgd and if it exists it will do the same with the message forwarding it setting now the associated ReceiveMote/SeqMsg that match with the SendMote/SeqMsg and so on until it arrives to the origin mote.

- The mote 0x3 (source one) will wait for an ack of the message; it will identify the message by the seqMsg, not by the targetAddr field, as there is no information in the destination node (0x8) about which mote is the sender. The first ack which arrives will be the fastest route that will possess bidirectional feature so it will update the entry in the table "Reachable Motes" with the target mote address and the SendMote/SeqMsg that it just received (that is the beginning of the route through the target mote, and it will provide the address where the message has to be sent and the sequence number for the next time it is needed to reach this target mote 0x8).

- If no ack messages are received after a certain time (that will be controlled with a timer based on trials, maximums and number of motes in the network), then a reported error will be passed to the user application alerting the destination can not be reached.

- For every ack message received in each mote (even if it will be forwarded), then assumes the route has been established and the field "Usage" in the "Routing Table" will be set to 0.

- Phase 2 (Follow Route): The mote 0x3 have information about the route in the "Reachable Motes" table (see Table 5.1) to reach 0x8, then:
  - Look for the target mote, get the pair SendMote/SeqRoute, and send a message TOS_MHoppingMsg (see Figure 5.1) to the SendMote address with:

    targetAddr=0x8
    senderAddr=0x3
    seqMsg=value global variable "sequence" for 0x3
    seqRoute= SeqRoute (send)
    type=FOLLOW_ROUTE
    data= nested data from the user message

  - The mote which receives it will identify the fields of the message with its RecvMote/SeqRoute and will find its forward pair SendMote/SeqRoute. It will fill the fields and forward it, incrementing the Usage field in the table "Routing Table" (see Table 5.2).

  - When it arrives to the target mote (check the targetAddr field) the reverse process will be done, sending an ack message to identify the message has been received and the route is still valid, like this:

    targetAddr=null (no info)

senderAddr=0x8
seqMsg=value global variable “sequence” for 0x8
seqRoute= SeqRoute (received)
type=ACK_FOLLOW_ROUTE
data= none

- o The source mote waits for the ack an established time; it checks the seqMsg & senderAddr fields to verify the ack is for the mote because of the lack of information in the targetAddr field.
- o If there is no ack from the message sent through the pair SendMote/SeqRoute for the source mote after a certain time (timer) then it will start the discovery process above.

- Phase 3 (Garbage Collector): This phase is oriented to eliminate the non valid routes on the “Routing Table”, routes which are not used anymore or routes which were created but not used ever because they were not fast enough. This process will keep the table at the minimum size possible in order to optimize searches, and consequently increase the routing speed.
    - o Every certain number of messages received (forward), or when the size of the table is more than a certain threshold, the table will be searched and entries with the field Usage set to 0 will be deleted.
    - o The table then will be sorted by Usage field in decreasing mode to keep the most frequently used routes the first entries.
    - o All this process will be performed as an atomic operation to avoid concurrency problems, so the messages being received will be queued until the process finishes.
    - o Timestamp could be used as another field in the table to delete non recently used routes but instead of that, every fixed interval time the Usage field will be decreased in 1 unit, so that will guarantee all the routes non being frequently used to reach the 0 value and be deleted in the next garbage process.

5.5- Features and drawbacks of the protocol

- The protocol could be improved adding more knowledge of the network to the motes in between a route, creating sub-routes when the acks arrives to each mote, creating entries in the table Reachable Motes (see Table 5.1) of these motes to reach the mote being requested. It has not be created in this first version of the protocol because it is thought there will be motes which will act just as routers, then the "Reachable Motes" table will be not useful and the memory will be wasted.

- Depending on the nature of the network, the new protocol will be more successful than the one implemented now in the TinyOS v1.x, but it will depend on factors like mobility of the nodes and number of messages being sent per time unit. As soon as the motes moves changing its action radio at a speed of less than 40 seconds, leaving neighbour radios, the number of messages will increase due to the need of looking for a new route in every message trying to be sent ad not receive and ack message.

- According to the characteristics of the application to be developed one of both multihop protocols could be used, multiplexing them or even a combination of both (hybrid protocol) could be created.

- The lack of information of the source node address in the destination node can be solved by inserting a new field in the structure of the "TOS_HoppingMsg" message (see Figure 5.1), like "int16_t sourceAddr" or the address from the source node can be nested in the data field, in the structure of the user message; the insertion of the source address as a field of the user structure message will be a requirement at the time of using the Hopping Multihop component.

Chapter 6 – Developing the protocol on Wireless Sensor Networks

6.1- Introduction

Although there are more technologies and developers of wireless sensor networks, the most well known and pioneer institution working on that is the TinyOS Intel Berkeley group, developers of the TinyOS operating system [2]. They are in close collaboration with the company Crossbow Technologies [3] which is producing a big diversity of devices like motes, gateways… and uses TinyOS to create its own applications.

For the purposes of this project it has been used TinyOS as the operating system, nesC as its associated programming language and hardware devices from Crossbow Technologies (motes, sensors and programming boards).

In this section it will be presented the hardware and software used, as well as the steps to start up from the first approach to WSN to the process of implementing the protocol. Besides it will be commented the difficulties or typical problems which appeared. It is believed that this chapter is a good starting point for anyone in this technology.

6.2- Hardware

6.2.1- Motes

For the purpose of this research it has been used 7 MICA2 motes from the company Crossbow Technologies [3]. This company produces wide range of sensing devices

In figure 6.1, it can be seen a MICA2 mote. It is composed by a board where it is integrated the connectors, processor, leds, memory components, switches, radio devices and a big unit connected to the board where it is placed 2 AA batteries which provide the power.

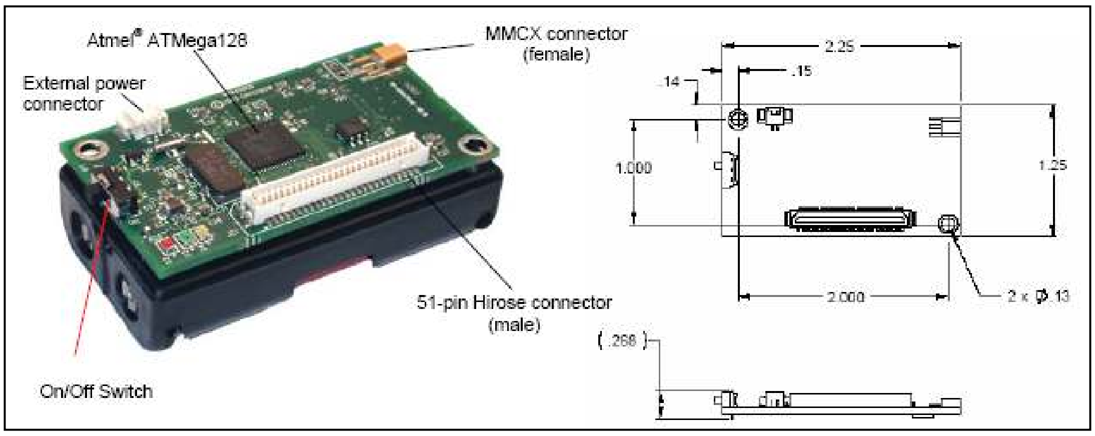
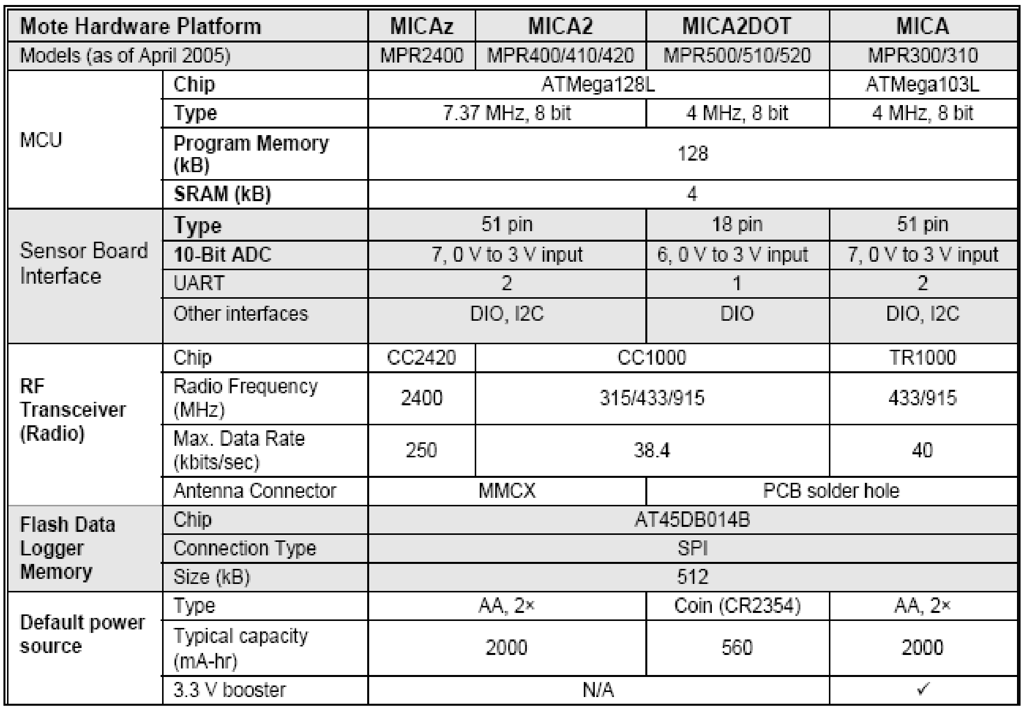


Figure 6.1: Left: Photo of a MICA2 (MPR4x0) without an antenna. Right: Top and plan views showing the dimensions and hole locations of the MICA2 PCB without the battery pack. [34]

The processor in MICA2 mote [35] is the Atmel ATmega 128L low power microcontroller. It has two modes of processing: active mode where its current draw is 8mA and sleep mode with 15µA.

In sleep mode MICA2 motes are expected to have a battery life of over 1 year with the 2 AA batteries. On the other hand, in active processor it depends on the processing operations, message sending rate but usually it reduces the lifetime exponentially.

Considering memory specifications (see Table 6.1) the MICA2 mote is characterized by a Program Flash Memory of 128Kb, where the applications are stored, another memory module of 512 Kb (flash data logger) that it is usually used to save sensor data and finally a 4 Kb SRAM memory for execution purposes.



Mote Hardware Platform		MICAz	MICA2	MICA2DOT	MICA
Models (as of April 2005)		MPR2400	MPR400/410/420	MPR500/510/520	MPR300/310
MCU	Chip	ATMega128L			ATMega103L
	Type	7.37 MHz, 8 bit		4 MHz, 8 bit	4 MHz, 8 bit
	Program Memory (kB)	128			
	SRAM (kB)	4			
Sensor Board Interface	Type	51 pin		18 pin	51 pin
	10-Bit ADC	7, 0 V to 3 V input		6, 0 V to 3 V input	7, 0 V to 3 V input
	UART	2		1	2
	Other interfaces	DIO, I2C		DIO	DIO, I2C
RF Transceiver (Radio)	Chip	CC2420	CC1000		TR1000
	Radio Frequency (MHz)	2400	315/433/915		433/915
	Max. Data Rate (kbits/sec)	250	38.4		40
	Antenna Connector	MMCX		PCB solder hole	
Flash Data Logger Memory	Chip	AT45DB014B			
	Connection Type	SPI			
	Size (kB)	512			
Default power source	Type	AA, 2×		Coin (CR2354)	AA, 2×
	Typical capacity (mA-hr)	2000		560	2000
	3.3 V booster	N/A			✓

Table 6.1: Mote Specifications Summary [34]

Communication in the MICA2 mote is leaded by a max. data rate of 38.4 Kbits/sec which operates on this range of frequencies: 315/433/915 MHz which are part of the Industrial Scientific and Medial band (ISM). For this research it has been used the MPR 400 MICA2 mote which operates at 900 MHz. The radio transmission range is within tens of meters (500-1000 ft) depends on the battery and obstacles, while drawing 27mA, [35]. The radio stack uses carrier sensing to control access to the wireless medium (CSMA). However, it does not enforce any collision detection, except that it discards messages which appear to be corrupt. There is no automatic retransmission of corrupt messages.

In most mote applications, the processor and radio run for a brief period of time, followed by a sleep cycle. Applications which use routing are lean to be in active mode more often, receiving, and transmitting data, consequently, applications which have a higher transmission rate (e.g. ad hoc multihop) will have a more reduced battery life.

6.2.2- Programming Board – Gateway

The programming board used to program the MICA2 motes was the MIB510 serial interface board from Crossbow Technologies [3] (see Figure 6.2).

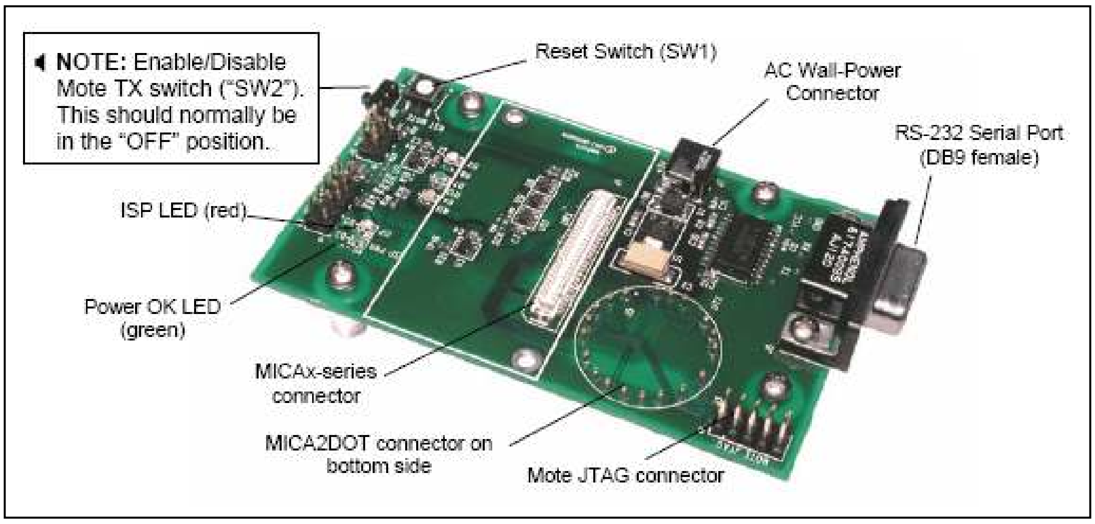

NOTE: Enable/Disable Mote TX switch ("SW2"). This should normally be in the "OFF" position.
Reset Switch (SW1)
AC Wall-Power Connector
RS-232 Serial Port (DB9 female)
ISP LED (red)
Power OK LED (green)
MICAx-series connector
MICA2DOT connector on bottom side
Mote JTAG connector

Figure 6.2: Programming Board MIB510CA [34]

According to [35], the MIB510 has an on-board in-system processor (ISP) -an Atmega16L located at U14- to program the Motes. Code is downloaded to the ISP through the RS-232 serial port. Next the ISP programs the code into the mote. The ISP and Mote share the same serial port. The ISP runs at a fixed baud rate of 115.2 Kbaud. The ISP continually monitors incoming serial packets for a special multi-byte pattern. Once this pattern is detected it disables the Mote's serial RX and TX, then takes control of the serial port.

The MICA2 motes are placed in the MICAx-series 51 pin connector for programming or gateway purposes.

It uses a RS-232 serial port to connection to connect to the serial port of the computer for programming and gateway purposes.

When the board is used for programming motes, the switch "SW2" should be placed in ON position, avoiding data coming from outside into the laptop (but it is not mandatory). If the board used as a gateway the switch "SW2" must be OFF to allow data coming from the motes into the computer.

The reset switch (SW1) is very useful to restart applications in motes or when a mote is not responding; it restart first the board ISP and after the mote.

The Jtag connector is used for in-circuit debugging.

The board can take the power either from the AC Wall-Power connector (it has an on-board regulator that will accept 5 to 7 VDC, and supply a regulated 3 VDC to the motes) or from the batteries of the mote placed into it (that will consume the batteries from the mote faster).

It has 3 leds in the motes which act as the leds in the mote placed on the board or as an indication of the state of the programming mode.

Finally it is advised to place the switch of the mote in OFF position when there is external power in the programming board.

6.2.3- Sensor Boards

Those devices are in charge of the sensing process. There is a huge variety for different sensing processes like for e.g.: acceleration, vibration, gyroscope, tilt, magnetic, heat, motion, pressure, temp, light, moisture, humidity, barometric; besides it also exists actuators like for e.g.: mirrors, motors, smart surfaces, micro-robots.

In the project it was used 7 MICA Sensor Boards -MTS300CA- (see Figure 6.3) from Crossbow Technologies [3].

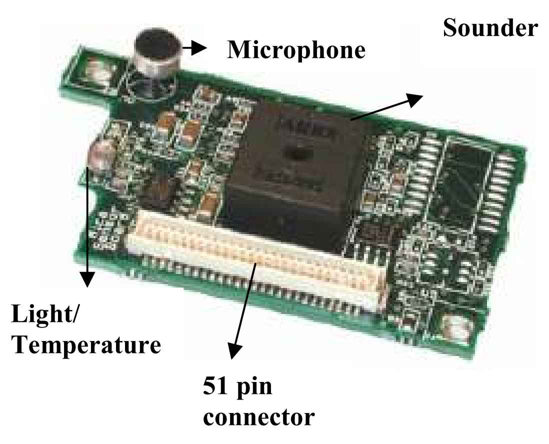


Figure 6.3: MICA Sensor Board MTS300CA [36]

The 51 pin connector is connected to the 51 pin connector in them mote once they are programmed. The data retrieved by the sensors is available for the applications in the mote using a 10 bit analogue/digital converter.

In this model of sensor [36] the light and temperature come integrated in the same measure component, so it must be set to on one of them in order to avoid collisions in the A/D converter channel. Besides, there are a microphone for acoustic ranging and recording, and a sounder which is a simple 4 KHz buzzer.

6.3- Software

TinyOS (see Section 2.6) was the operating system used to configure the MICA2 motes. Windows XP was chosen as the platform to operate TinyOS, instead of Linux. TinyOS is available in a auto installable package for windows and for most of its versions. With the packet it includes the operating system TinyOS plus the nesC programming language compiler, the java version 1.4 JDK and cygwin (tool to emulate Linux). TinyOS is installed within a directory in your hard drive with the structure of Linux directories and can be accessed through windows or through command line with the cygwin tool.

The developers of TinyOS have released version 2.0 in July 2006 but is not tested properly yet. Previous versions like 1.15 or 1.11 are advised but for the purposes of this project it was selected version 1.1.0. This version is very stable and although it has had been produced modifications respect to higher versions, it does not affect for the purpose of this project; the developing of the ad hoc protocol. As it was explained in Chapter 4, both multihop protocols were already created in version 1.1.0 and they last until version 2.0 where new protocols for aggregation and dissemination has been developed.

Figure 6.4 show the tree directory structure of the TinyOS. The Hopping protocol will be developed under the subdirectory “tos/lib/RouteHopping”. An application created for the purpose of evaluating the protocol will be places in subdirectory “tinyos-1.x/apps” called HOPPING.

Besides, TinyOS offers a documentation directory “tinyos-1.x/doc” where is stored the results of a documentation generator (similar to javadoc) which creates api’s from your own applications, just as easy as typing “make docs <platform(mica2)>”. Besides the tool Graphviz generates a graph with the wiring (links) among components.

The “/tos” subdirectory is the system directory where the libraries, drivers, types and interfaces are stored. This is where the internal layers are structured in folders and it is very useful to learn about programming and how to use components.

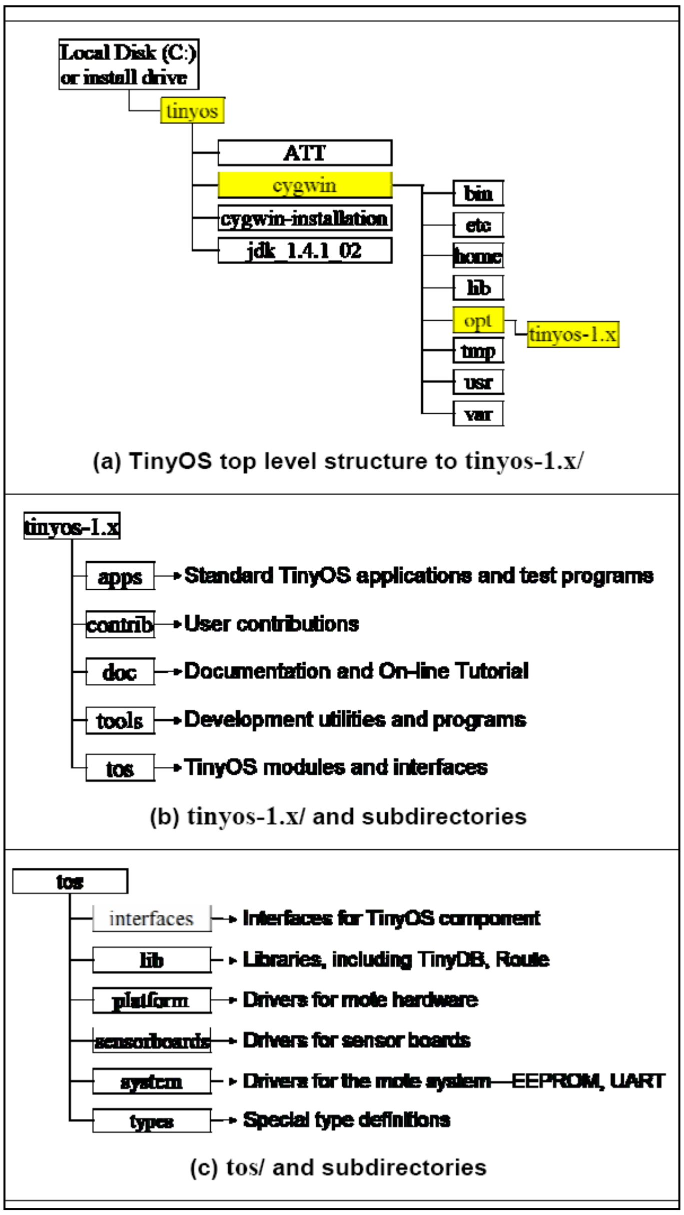

Local Disk (C:) or install drive
tinyos
ATT
cygwin
cygwin-installation
jdk_1.4.1_02
bin
etc
home
lib
opt
tinyos-1.x
tmp
usr
var
(a) TinyOS top level structure to tinyos-1.x/
tinyos-1.x
apps
Standard TinyOS applications and test programs
contrib
User contributions
doc
Documentation and On-line Tutorial
tools
Development utilities and programs
tos
TinyOS modules and interfaces
(b) tinyos-1.x/ and subdirectories
tos
interfaces
Interfaces for TinyOS component
lib
Libraries, including TinyDB, Route
platform
Drivers for mote hardware
sensorboards
Drivers for sensor boards
system
Drivers for the mote system—EEPROM, UART
types
Special type definitions
(c) tos/ and subdirectories

Figure 6.4: TinyOS and Subdirectory Map [13]

Moreover, tools to operate in TinyOS (most of them developed in java) can be found in “tinyos-1.x/tools”. Some of the most useful tools are:

- **TOSSIM**: A discrete event simulator for TinyOS [37]
- **(MIG) Message Interface Generator**: This tool generates stubs to encode and decode TinyOS messages.
- **Serial Forwarder**: it is used to read packet data from a computer’s serial port and forward it over a server port connection, so that other programs can communicate with the sensor network via a sensor network gateway. It does not display the packet data itself (although it was modified to do it) and updates the packet counters (read and written).
- **MessageInjector**: Useful tool to inject packets in the network; just select type of message (depending on the application installed in the motes), tell destination mote and send the message.
- **Surge**: Java application that draw the topology of the network which is using multihop components. It needs to have installed in the motes the surge application which sends message every certain time through the network to the base station using the routing component “multihopRouter”.

6.4- Start up a WSN with TinyOS and Crossbow motes

Installation of TinyOS is pretty easy under Windows environment, just follow the steps. It is advised to install it in the root directory (c:/) to increase performance and it is required to have about 1 Gb free space in your hard drive for the installation although once installed it takes about 550 Mb.

Once installed it should be tested if the installation has been successful; for that under the installation directory, go to this path “/tinyos/cygwin/opt/tinyos-1.x/tools/scripts” and run the script “toscheck”. If it ends with “toschek completed successful then the installation is working. Sometimes it happens there was a version of java already installed and it produces conflicts; this could be produced because the CLASSPATH is not well configured for the java version; check environment variables (Add in “Path” the new route for the java directory like this: *Path=;D:/tinyos/java/j2sdk1.4/bin*) and if still remains the error:

- It could happen it is needed to set the environment variable CLASSPATH to “.”
- Delete Superior Java Versions

Once it is installed, create the MakeLocal file in folder /apps, this will set up the environmental developing parameters to program the motes like frequency, group id for the set of motes being programmed and identify the serial port (see Figure 6.5).

```
#Makelocal File
# Created by Ricardo Simon Carbajo
PFLAGS += -I%T/../beta/MyBetaCode
DEFAULT_LOCAL_GROUP = 0x7e
PFLAGS += -DCC1K_DEF_FREQ=900000000
MIB510=COM1
```

Figure 6.5: Makelocal file in folder “/apps” in TinyOS

Some java applications may require compilation; simply execute the makefile file under “/tos/java/net”.

In order to compile your first application, it should be compiled depending on the platform being used; in this case “mica2”. Although there is an option to compile all the applications, it is advised to go to the application you wish to compile, for instance, go to “/apps/blink” and type “*make mica2*”; that will generate a folder called “build” with the executables (srec), which should be installed in the motes.

To program the motes with the application:

- Programming board switch should be switched OFF
- Place the mote to program in the board, switched to OFF
- Connect serial port to pc.
- Close programs like SerialForwarder that uses the port (e.g.:COM1).
- In the folder where the application is type:
    - *MIB510=COM1 make reinstall.<num_mote> mica2*

This option just load the executables into the mote

  - *MIB510=COM1 make install.<num_mote> mica2*

    This option compiles the application and load into the mote (see Figure 6.6 for a successful compilation and loading).

MIB510=COM1 indicates the programming board is the MIB510 and it uses the serial port COM1.

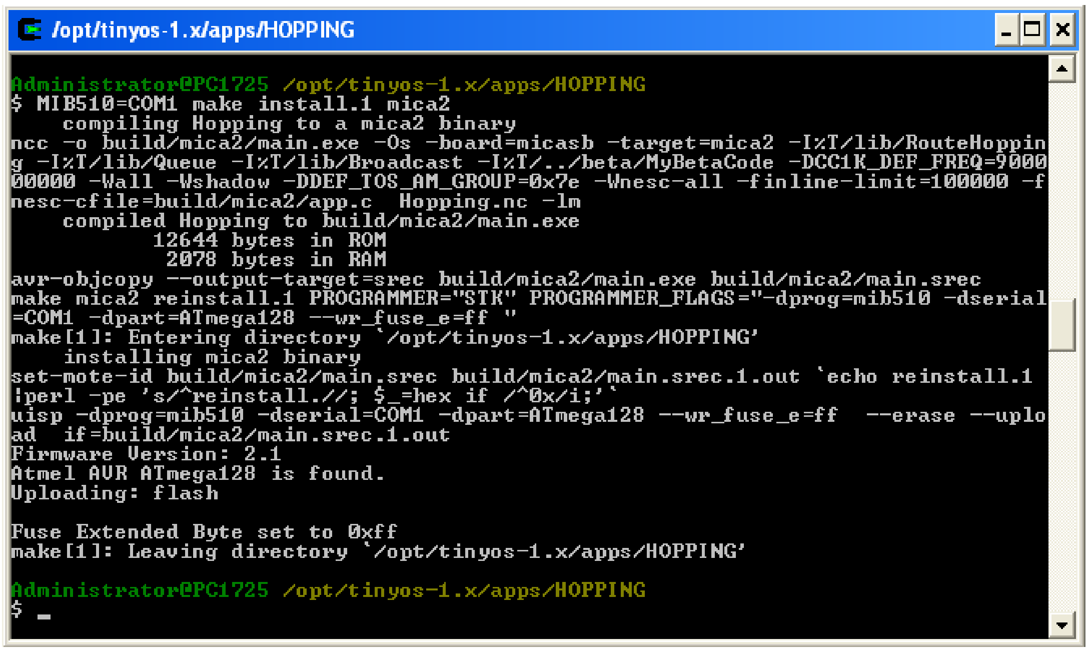
<*num_mote*> is the address the mote will have; the address 0x0 os reserved for the base mote, the one who will be placed in the motherboard and act as a gateway between radio communication and serial port.

- If problems are experienced you should export the shell variable MOTECOM with the route to read from the serial with:
  - export MOTECOM=send@COM1:mica2 or
  - export MOTECOM=send@COM1:<freq>
- Sometimes the motes or programming board do not respond, in that case, loading phase will throw an error. Possible solutions can be: reset button in programming board, change from mote, try to load a simple application like "blink", restart the cygwin, check serial port properties and reinitiate or even restart the computer.

There are applications like "blink" which works without radio communication. Other use radio and in order to monitor the messages, a mote with the application "TOS_Base" and address 0x0 should be placed in the programming board. Then the SerialForwarder tool should be run from the "..\opt\tinyos-1.x\tools" like this:

java net.tinyos.sf.SerialForwarder -comm serial@COM1:57600

Then the program will count the number of messages being received (see Figure 6.7).

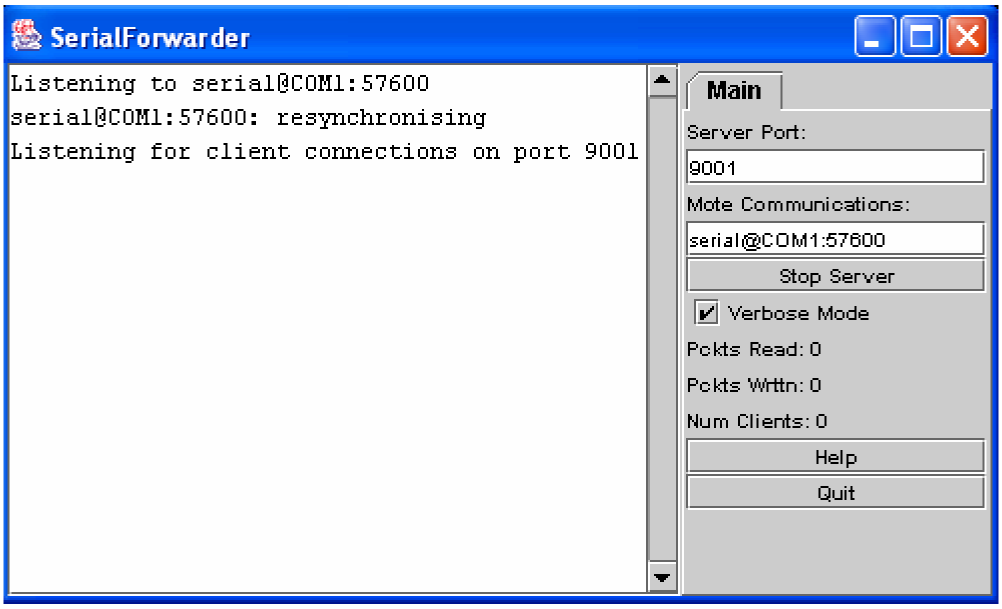


```
Administrator@PC1725 /opt/tinyos-1.x/apps/HOPPING
$ MIB510=COM1 make install.1 mica2
    compiling Hopping to a mica2 binary
ncc -o build/mica2/main.exe -Os -board=micasb -target=mica2 -I%T/lib/RouteHoppin
g -I%T/lib/Queue -I%T/lib/Broadcast -I%T/../beta/MyBetaCode -DCC1K_DEF_FREQ=9000
00000 -Wall -Wshadow -DDEF_TOS_AM_GROUP=0x7e -Wnesc-all -finline-limit=100000 -f
nesc-cfile=build/mica2/app.c  Hopping.nc -lm
    compiled Hopping to build/mica2/main.exe
           12644 bytes in ROM
            2078 bytes in RAM
avr-objcopy --output-target=srec build/mica2/main.exe build/mica2/main.srec
make mica2 reinstall.1 PROGRAMMER="STK" PROGRAMMER_FLAGS="-dprog=mib510 -dserial
=COM1 -dpart=ATmega128 --wr_fuse_e=ff "
make[1]: Entering directory `/opt/tinyos-1.x/apps/HOPPING'
    installing mica2 binary
set-mote-id build/mica2/main.srec build/mica2/main.srec.1.out `echo reinstall.1
|perl -pe 's/^reinstall.//; $_=hex if /^0x/i;'`
uisp -dprog=mib510 -dserial=COM1 -dpart=ATmega128 --wr_fuse_e=ff  --erase --uplo
ad  if=build/mica2/main.srec.1.out
Firmware Version: 2.1
Atmel AVR ATmega128 is found.
Uploading: flash

Fuse Extended Byte set to 0xff
make[1]: Leaving directory `/opt/tinyos-1.x/apps/HOPPING'

Administrator@PC1725 /opt/tinyos-1.x/apps/HOPPING
$ _
```

Figure 6.6: Compilation & Load application into a mica2 mote.



```
Listening to serial@COM1:57600
serial@COM1:57600: resynchronising
Listening for client connections on port 9001
```

Server Port: 9001

Mote Communications: serial@COM1:57600

[✓] Verbose Mode

Pckts Read: 0

Pckts Wrttn: 0

Num Clients: 0

Figure 6.7: SerialForwarder Tool

It would be interesting to program some nodes with the "Surge" applications to obtain mutihop routing. In order to do that, compile as above and load applications into the motes. Load one mote with surge application and address 0 and place it in the programming board. Then execute SerialForwarder and afterwards run the client program, which will join the SerialForwarder to receive packets, to draw the motes for the surge application like this (go to folder "..\opt\tinyos-1.x\tools"):

java net.tinyos.surge.MainClass <GroupId>

GroupId is the specified in the Makelocal, *0x7e*

The motes will start to converge in a tree-based routing schema, sending packets every 2 seconds through the topology to reach the base mote (see Figure 6.8).

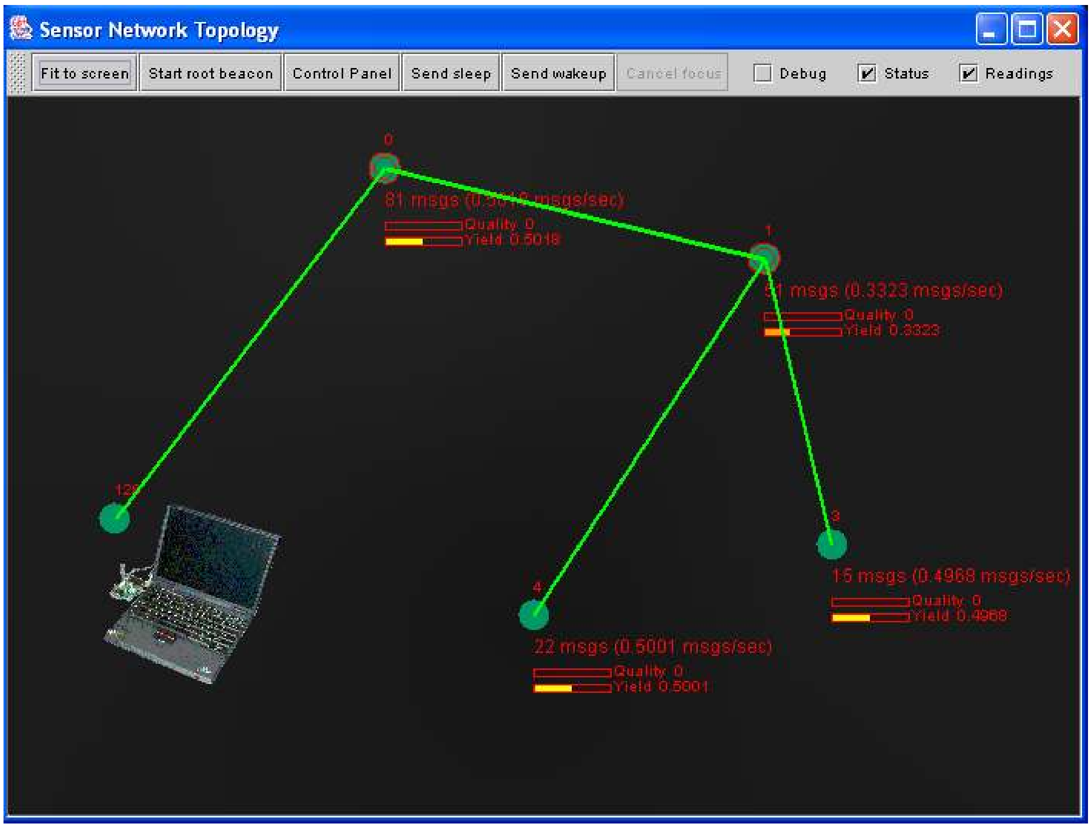


Figure 6.8: Surge application using multihop routing in TinyOS

After that and following the tutorial in the TinyOS, you are ready to start developing your own applications!

6.5- Design and Implementation of Hopping

The design of the architecture of the new protocol was based on the existing routing architecture. In fact it is provided most of the interfaces of the existing configuration file (MultiHopRouter), which provides the interfaces to perform multihop routing in an application (see Chapter 4). It is followed the same architecture and used the same name for the configuration component, to make easy testing or multiplexing between components. The new issue which is different from the existing component diagram is that the link estimation component (MultiHopLEPS) is suppressed and all the logic is concentrated in the HoppingEngineM component (substitute MultHopEngineM).

Both components are stored in the library folder (see Appendix: CD-ROM):

"opt\tinyos-1.x\tos\lib\RouteHopping"

The configuration component (MutiHopRouter) wires the commands and events from HoppingEngineM with the commands and events from the components for communication (GenericCommPromiscuous and QueuedSend). Besides it connects components to perform other functions like (TimerC and LedsC). Furthermore the configuration file provides the next interfaces to perform routing: Receive, Send, Interface and Snoop plus the StdControl interface to initiate the routing components (see Figure 6.9).

```
includes AM;
includes Hopping;

configuration MultiHopRouter {
  provides {
    interface StdControl;
    interface Receive;//[uint8_t id];
    interface Intercept;//[uint8_t id];
    interface Intercept as Snoop;//[uint8_t id];
    interface Send;//[uint8_t id];
  }

}
implementation {
  components HoppingEngineM, GenericCommPromiscuous as Comm,
    QueuedSend, TimerC, LedsC;

  StdControl = HoppingEngineM;
  Receive = HoppingEngineM;
  Send = HoppingEngineM;
  Intercept = HoppingEngineM.Intercept;
  Snoop = HoppingEngineM.Snoop;

  HoppingEngineM.SubControl -> QueuedSend.StdControl;
  HoppingEngineM.CommStdControl -> Comm;
  HoppingEngineM.CommControl -> Comm;

  HoppingEngineM.Leds  -> LedsC;

  HoppingEngineM.SendMsg -> QueuedSend.SendMsg[AM_HOPINGMSG];
  HoppingEngineM.ReceiveMsg -> Comm.ReceiveMsg[AM_HOPINGMSG];
  HoppingEngineM.Timer -> TimerC.Timer[unique("Timer")];
}
```

Figure 6.9: MultiHopRouter configuration for the Hopping protocol

The HoppingEngineM component manages all phases of the protocol and it imports the "hopping.h" file which contains definitions of tables (see Section 5.2) as well as the structure of the HoppingMsg (see Section 5.3). Detailed explanation about each events, commands and functions can be found at (see Appendix: CD-ROM):

"opt\tinyos-1.x\tos\lib\RouteHopping/HoppingEngineM.nc"

The graph of components generated with the tool Graphviz can be seen in Figure 6.10; it shows all the wiring components and what interfaces are used and provided. Besides all the documentation for the Hopping routing components can be seen in (see Appendix: CD-ROM):

"opt\tinyos-1.x\doc\nesdoc\mica2"

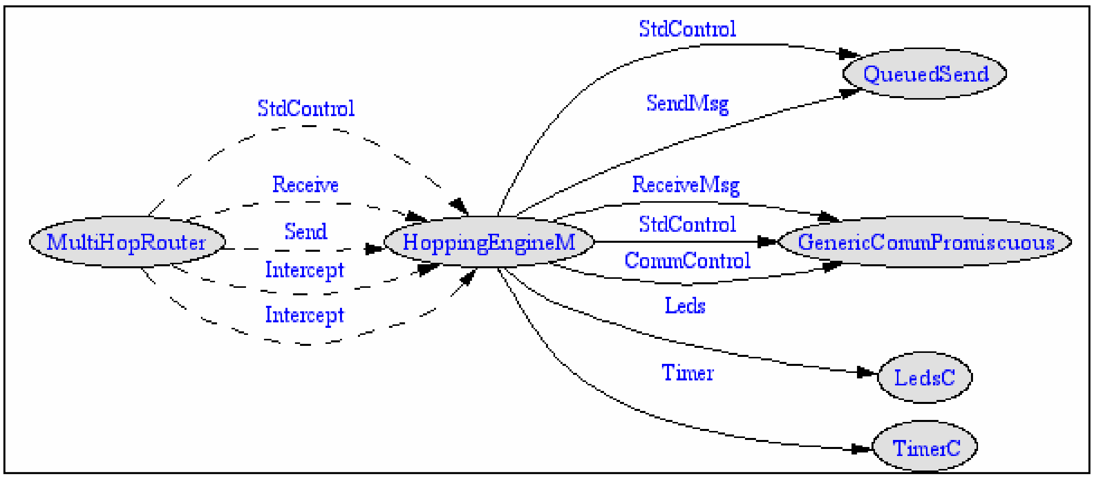


Figure 6.10: Component Diagram for the Hopping protocol.

In order to demonstrate the working of the routing protocol, it was created an application called Hopping which is explained in Chapter 7. Figure 6.11 shows the component diagram where it can be seen how it is being used the MultiHopRouter configuration to provide routing. The code can be found in the folder (see Appendix: CD-ROM):

"opt\tinyos-1.x\apps/HOPPING"

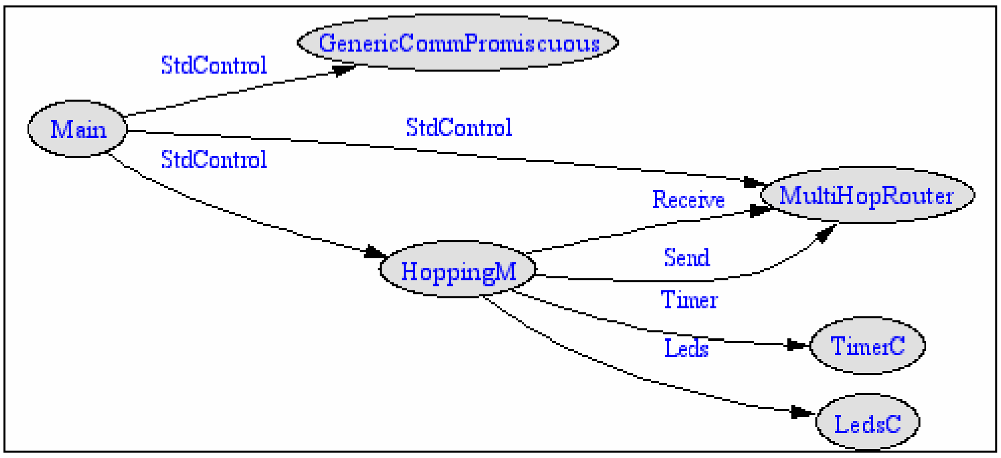


Figure 6.11: Component Diagram for the Hopping application which uses the Hopping protocol (MultiHopRouter).

6.6- Problems experienced

6.6.1- Problems programming motes

- Experienced problems with Tinyos 1.1.11 (auto install). It seems the motes don't get programmed properly (Error: fuse error flash 0x8a …). As well, it doesn't detect the makelocal configuration file in the "/apps" directory. It can be an incompatibility problem between versions although that happens in the starting with TinyOS 1.1.0 but it suddenly fixed. There are some possible solutions in Internet, possible procedures but none of them worked. Maybe, malfunction in TinyOS 1.1.11 installation.
- It's better to use "*MIB510=COM1 make install.X mica2*" than with the "reinstall.X" option, because it rebuild the application.
- It's useful sometimes to clean the "/build" folder in each application before doing "make clean" to prevent bad compilation and avoid overlapping in motes.
- In the Surge Application which uses Multihop modules:
    - The Base Node must be configured with the Surge.nc module and with id=0.
    - The SerialForwarder produces an exception when receives more than 7535 messages.

6.6.2- Problem using the multihop components

- It was experienced that the interface “Receive” in the module MultiHopEngineM.nc is not connected to the interface ReceiveMsg, so in order to receive messages is necessary to use events like “Intercept.intercept” or “Snoop.intercept”, because the events on these interfaces are the only ones signaled from the ReceiveMsg event, implemented in the module MultiHopEngineM.nc. SOLUTION: It should be signaled the event “Receive” from the event “ReceiveMsg” (see Figure 6.12).

- The special feature about the use of MultihopRoute configuration is that the interface “ReceiveMsg” is opened to be wired and must be wired with the type of message your application will handle, like:

```
multihopM.ReceiveMsg[AM_SURGEMSG]->Comm.ReceiveMsg[AM_SURGEMSG];
```

- Besides, the type of message selected for the application, like in Surge: AM_SURGEMSG, will affect the entire interfaces id’s “[uint8_t id]”. If the interface “Send[uint8_t id]” of the MultiHopRouter configuration is wired using the message id: AM_SURGEMSG, all the rest of interfaces like “Intercept[uint8_t id]” or “Snoop[uint8_t id]”,… will automatically just accept this type of messages. So the MultiHopRouter configuration accepts just 1 type of message for application for all the interfaces, except for the internal AM_MULTIHOPMSG.

```
event TOS_MsgPtr ReceiveMsg.receive[uint8_t id](TOS_MsgPtr pMsg) {
   TOS_MHopMsg *pMHMsg = (TOS_MHopMsg *)pMsg->data;
   uint16_t PayloadLen = pMsg->length - offsetof(TOS_MHopMsg,data);

          ……….

   // Ordinary message requiring forwarding
   if (pMsg->addr == TOS_LOCAL_ADDRESS) { // Addressed to local node

     //HERE COMES THE LINE OF CHANGE
     signal Receive.receive[id](pMsg,&pMHMsg->data[0],PayloadLen);

     if ((signal Intercept.intercept[id](pMsg,&pMHMsg->data[0],PayloadLen)) == SUCCESS)
     {
          pMsg = mForward(pMsg,id);
     }
   }
   else
   {
    // Snoop the packet for permiscuous applications
    signal Snoop.intercept[id](pMsg,&pMHMsg->data[0],PayloadLen);
   }

   return pMsg;
 }
```

And create the event Receive.receive to be signaled and that math with the interface provided:

```
default event TOS_MsgPtr Receive.receive[uint8_t id](TOS_MsgPtr pMsg,
                                                     void* payload,
                                                 uint16_t payloadLen) {
   return pMsg;
 }
```

Figure 6.12: Modifications (in bold) in the MutiHopEngineM component to allow functionality in the event Receive.receive.

Chapter 7 – Evaluation

The implementation of the algorithm has been done in nesC under the TinyOS operating system. Despite the use of a non specific editor (it could have been used the plug-in provided for Eclipse for programming in TinyOS [38]) and after wiring the components properly, making the components match, a compiled version was built for the mica2 platform to be deployed initially in 2 motes.

For the purpose of evaluating the protocol created (Hopping) in the routing layer, an application which uses the routing component was implemented. It was created an application that every certain time (2 seconds), created a message and send it to the node 0x2. Another application was created to receive this message and blink the red toggle if the message was for the local mote.

Initially the system should work with 2 motes and later the number of them will be increased.

It was configured a mote with the address 0x1 and loaded on it the application which sends a message to 0x2 every 2 seconds, using Hopping. The second mote was loaded with the application that received the message with destination equal to 0x2 and it was given the address 0x2, to successfully receive the message and then blink the red led indicating reception.

The motes were successfully loaded with the applications and the mote with address 0x2 was turned on first, waiting so for a message. The mote with address 0x1 was turned on afterwards.

If routing was working, the red led on the 0x1 will turn on after 2 seconds, then a discovery route process will be start to get the route to 0x2. Node 0x2 should receive message (NEW_ROUTE message) from 0x1, prepare the ack message (ACK_NEW_ROUTE) and send it back to 0x1. Then the mote 0x1 should receive the ack and send the message that was requested to send following the route already created. Then 0x2 will receive the message identify it is for it and blink the red led to identify it has received the message. An ack message from 0x2 to 0x1 should then be sent to confirm the link is still valid.

The results were not exactly the expected ones but it was shown that not everything was failing; the red led on 0x1 blink after two seconds, then the message was received by 0x2 and the red led blinked. Amazingly, the red led on 0x1 keeps blinking after 2 seconds but after the first message the mote 0x2 did not blink anymore.

In order to verify where the system was failing, the debugging system was based in leds acting as prints, indicating that the execution had reached this part of the code, that a message had been sent or received and that commands were executed and events were signaled.

Using green and yellow one it was followed the execution of mote 0x1. It was concluded, the discovery phase was successfully completed. Then, it was tested that the message followed the route already established in the discovery phase through 0x2. After that it was successfully tested that the ack from 0x2, confirming that the route was still working, was received by 0x1. Then the process of routing had working but just for the first message, so why?

Using leds it was observed that although the red was blinking every two seconds in the mote 0x1, the event which indicates the successful sending of a message (event sendDone) was not signaled anymore (green led, just changed twice, one for discovery phase and another for the message being sent).

It is believed it could be a problem of concurrency in the sending process or it could be a pointer not well returned from a command call or receive event. Besides, the code is using a global variable to generate synchronization in the sending process, so if there is an already sending process another one can interrupt it. Timers that controlled the process of not receiving an ack massage after an estimated maximum time was removed to avoid more hardware event collisions (produce more concurrency and can preempt tasks).

Motes with different addresses and configured to toggle the yellow led when any message was received and the green led when the received message was a broadcast one, were included in the experiment, demonstrating that the discovery phase works with broadcast and that the acks followed paths of already created routes.

It is being restructured the sending process to isolate it in a task and keep in a queue messages to be sent. That will avoid all type of concurrency problems.

As a final evaluation it can be commented that the protocol develops the discovery phases and the follow route phase successfully, so entries are created in tables successfully. The protocol idea seems to be correct and the failure is believed to be in a hardware event concurrent problem.

Because of the lack of time and the hard process of debugging hardware with leds, the protocol is not fully working.

Chapter 8 - Conclusions and Future Research

After being working with MICA2 motes and TinyOS over Wireless Senor Networks I have to conclude this technology is quite tricky. Because of the component-based event-driven programming paradigm used to create the applications, and the new way of wire components, it has to be adopted another vision of programming, nor object oriented, neither pure imperative. Besides, working with hardware at a non high level is a handicap; flashing memories can throw strange errors which sometimes can only be solved by resetting. Although it takes time and it can be exasperating the exponential learning curve make you understand, with every concept, the whole of the system much better and create a big picture of how it works.

The debugging process is an issue where research should be focused. Although there are ways of debugging like using simulators, attach hardware to the gateway or using leds, when the debugging process gets harder and there is the need of getting values from variables at running time in a mote, there is nothing to do rather than supposing or using leds.

The new protocol developed in this dissertation (Hopping) has not been fully tested but it is believed the protocol will help to save battery life in motes, managing in an efficient way the resources available. The protocol will offer another way of distributed communication, peer to peer, where there is no hierarchy and all motes can influence each other. It is thought the protocol can be very useful in this type of applications where there is no gateway and the motes have to create auto-organized networks to retrieve data, communicate each other, take decisions and act consequently. Although the protocol can work in all different types of network conditions, there are some limitations where the protocol does not behave in an optimum way, compare to the protocol which is implemented in version 1.x from TinyOS. Among these limitations it is the mobility of motes; the protocol works in an ad hoc basis but if the mobility of the motes and the message transmission rate is so high that the discover phase has to be done every time a message is sent, then the protocol will not perform as good as the existing one. In that case a multiplexing between both protocols could be done based on mobility of the network.

It should be put effort in getting the protocol fully working and well tested. It has to be checked concurrency, mainly in the sending process and optimize the use of tasks. Moreover it should be evaluated the growing speed of the routing table in different network conditions and consequently tune the garbage collector phase parameters, to avoid overheads in the routing process; memory increasing has to be controlled.

Evaluate the protocol in comparison to the existing one would be very challenging and can provide an idea of a possible hybrid protocol with the best features of both.

As it is an emerging technology, it is still in the early process of development. Tools to make the programming and debugging tasks easier are being developed as well as creating multipurpose applications to interact with motes in a high level user-oriented programming way.

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Appendix: CD-ROM

The CD-ROM contains:

- The install shield wizard for TinyOS release 1.1.0 (Windows).

- The whole structure of the TinyOS directories starting in folder "/opt" where it can be found:
    - HOPPING application, which uses the new protocol; it can be found under the path: "/opt/tinyos-1.x/apps".
    - RouteHopping folder, which contains the routing components of the new protocol; it can be found under the path: "/opt/tinyos-1.x/tos/lib".
    - Documentation of the new protocol auto-generated with the Graphviz tool can be found in path: "/opt/tinyos-1.x/doc/nesdoc/mica2/index.html".
    - Typical applications and other projects created during the project like Surge2 (a modification of the Surge application).

- The electronic version of this document in pdf format.