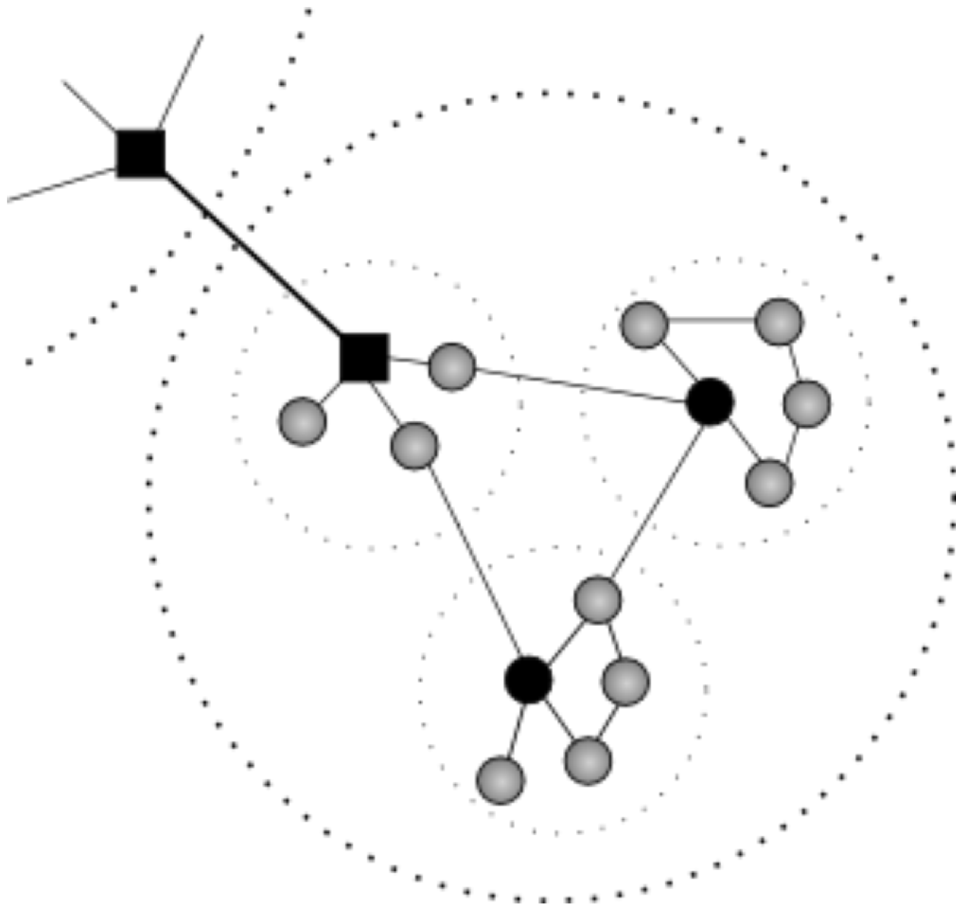
CHALMERS



Clustering algorithms for Wireless Sensor Networks and Security threats

Master's Thesis under Erasmus programme

CARLOS ALEIXANDRE TUDÓ

Department of Computer Science and Engineering
Division of Distributed Computing and Systems group
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2010

Master's Thesis 2009:10

The Author grants to Chalmers University of Technology and University of Gothenburg the non-exclusive right to publish the Work electronically and in a non-commercial purpose make it accessible on the Internet.
The Author warrants that he/she is the author to the Work, and warrants that the Work does not contain text, pictures or other material that violates copyright law.

The Author shall, when transferring the rights of the Work to a third party (for example a publisher or a company), acknowledge the third party about this agreement. If the Author has signed a copyright agreement with a third party regarding the Work, the Author warrants hereby that he/she has obtained any necessary permission from this third party to let Chalmers University of Technology and University of Gothenburg store the Work electronically and make it accessible on the Internet.

Clustering algorithms for Wireless Sensor Network and security threats

CARLOS ALEIXANDRE TUDÓ

© CARLOS ALEIXANADRE TUDÓ, June 2010.

Examiner: Andreas Larsson

Chalmers University of Technology
University of Gothenburg
Department of Computer Science and Engineering
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Department of Computer Science and Engineering
Göteborg, Sweden June 2010

MASTER'S THESIS 2009:10

Clustering algorithms for Wireless Sensor Networks and Security threats

CARLOS ALEIXANDRE TUDÓ

Department of Computing Science and Engineering
Distributed Computing and Systems Research Group
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2010

Clustering algorithms for Wireless Sensor Networks and Security threats

© CARLOS ALEIXANDRE TUDÓ, 2010

Master's Thesis 2009:10

Department of Computing Science and Engineering
Distributed Computing and Systems Research Group
Chalmers University of Technology
SE-41296 Göteborg
Sweden

Tel. +46-(0)31 772 1000

Department of Computing Science and Engineering
Göteborg, Sweden 2010

Clustering algorithms for Wireless Sensor Networks and Security threats

CARLOS ALEIXANDRE TUDÓ
Department of Computing Science and Engineering
Distributed Computing and Systems Research Group
Chalmers University of Technology

Abstract

Since few years ago the interest of wireless sensor networks (WSNs) have been increasing. Furthermore a small battery sensors had appeared recently because of the miniaturization development. These new devices have a radio inside and a microprocessor, thus they can manage a big quantity of data. This new scenario has multiples advantages such as they can operate in hard conditions when the human can't do or can be set up in a broad kind of systems to monitore and analyze the data. Sensors are randomly deployed over the terrain and they have to self-organize in a small groups to achieve a good power saving, scalability and routing. Thereby we need a new clustering sensor's algorithms to organize these nodes in groups. In this thesis, we implement and test some clustering algorithms to obtain the latter features. We also study which are the security threats of our algorithm in order to see how vulnerable they are against malicious nodes and we will try to breakdown the system.

Keywords: WSN, Clustering algorithms, Security, TinyOS

Contents

Abstract iv

Contents v

Acknowledgements ix

1 TinyOS 1
- 1.1 TinyOS 2.1 1
- 1.2 NesC 1
- 1.3 TOSSIM 2
- 1.4 Our Workspace 3
- 1.5 Example of application 4
  - 1.5.1 Configuration file (HelloWorldAppC.nc) 4
  - 1.5.2 Module File (HelloWorldC.nc) 6
- 1.6 Configuring TOSSIM 8
- 1.7 Security 8

2 LEACH algorithm 11
- 2.1 Description 11
- 2.2 Protocol Specification 12
  - 2.2.1 Phase 1: Setup Phase 12
  - 2.2.2 Phase 2: Steady-State Phase 13
- 2.3 Example 13

3 Distributed cluster (Clique) algorithm 15
- 3.1 Description 15
- 3.2 Protocol Specification 15
- 3.3 Implementation 16
  - 3.3.1 Step 1: Local Maximum Clique 16
  - 3.3.2 Step 2: Ordering and Updating Maximum Clique 17
  - 3.3.3 Step 3: Obtaining Final Clique 18
  - 3.3.4 Step 4: Checking Clique Agreement 19

4 Distributed bounded-distance multi-clusterhead algorithm 21

4.1 Description 21
4.2 Protocol Specification 21
4.2.1 Phase one 22
4.2.2 Phase two 22
4.3 Example 24

5 New Distributed multi-clusterhead algorithm 27
5.1 Description 27
5.2 Protocol Specification 28
5.3 Example 29

6 Design problems 33
6.1 How to know who are my neighbours? 33
6.1.1 The realistic solution 34
6.2 Packet collisions 35
6.2.1 The broadcast ACK problem 36
6.3 Messages and Matrix type 37
6.3.1 Boolean Matrix 38
6.3.2 Integer Matrix 39
6.3.3 The solution adopted 40
6.4 Synchronization 41
6.5 Fragmentation 42
6.6 Data compression 43
6.7 Tree implementation 43

7 Security Analisys 47
7.1 Attacks in WSN 47
7.2 Security threats in TinyOS 49
7.3 LEACH Algorithm 50
7.3.1 HELLO flood attack 50
7.3.2 Sybil attack 50
7.3.3 Other attacks 51
7.4 Distributed cluster (Clique) Algorithm 51
7.4.1 Silence attack 51
7.4.2 HELLO, Sybil and Wormhole attacks 52
7.5 Distributed bounded-distance multi-clusterhead algorithm 52
7.5.1 Selective forwarding 52
7.5.2 Others attacks 53
7.6 New Distributed multi-clusterhead algorithm 53
7.7 Conclusions 53

Bibliography **55**

Bibliography **55**

Acknowledgements

Thanks to my family and Iris who always supported me throughout my career.

I would like also to say my thanks to my supervisor Philippas Tsigas and my advisor Andreas Larsson who helps me with practical processes.

1 TinyOS

TinyOS is a free and open source component-based operating system and platform targeting wireless sensor networks (WSNs). It is an embedded operating system written in the nesC programming language as a set of cooperating tasks and processes. The purpose is to incorporated into small devices.

1.1 TinyOS 2.1

We will use TinyOS as the operative system for our devices. The decision to choose it is because of is very power efficient . Power efficient is necessary for motes due to sensors have small-size battery, this means that they are energy-constrained and their batteries can't be recharged. Thus, energy is the most valuable resource and using TinyOS that is power-efficient we can achieve our motes more time alive. TinyOS reduces the energy consumption thanks to new internal architecture. For example in a tradition OS micro-kernel, we have large memory requirement, complex I/O subroutines, a lot of contexts switches... All of these operations requires among quantity of energy. To reduce this consumption TinyOS proposes a new easy, thin and low-consumption architecture. It changes all this heavy process to other more simples like: only one process (no process management), linear physical address space (no virtual memory), no software signals (only function call), no dynamic memory (to reduce the stack), direct hardware interrupts (no kernel interrupts), no kernel/user space differentiations, single share stack, etc. With it we can decrease the memory size and the system overload.

The operative system, has also a lot more features that makes it to be one of the most powerful embedded systems, but the aim of this thesis is it not to explain all of the system features.

1.2 NesC

NesC (network embedded systems C) is a dialect of the C programming language optimized for the memory limitations of sensor networks. This programming language is used to build applications for the TinyOS platform. It has two features that makes us to develop applications for TinyOS very easy and powerful: is component-based and event-driven. All nesC files has ".nc" extension.

Programs are built by modules (components), some of which present hardware abstractions layers (HAL) and other just high level applications. A component consists of three main things: frame, set of tasks and interfaces (command and events). Interfaces is the most important in the sense of how applications are organized and works. Components are connected each other using interfaces from the top layer to the bottom layer and it is the only way to access to the component. This kind model interfaces allows the system to have an efficient modularity. Moreover because of in the TinyOS internal core there aren't any signals, just call functions, these commands and events are very efficients.

Interfaces provides command functions. This mean that we can call this routine and the handler of the interface will execute the code of the command. Thus, as we can see, interfaces have to provide commands to let other components to use them. Commands are usually requests from the upper layers and handled by the lower layers.

The second important feature is that nesC is event-driven. This means that the execution of the program is determined by events (i.e: sensors input, timers, etc). Coming back to the components model that we talk before, that means events is just the events code of our interfaces. We must implement the code for these events and when this event will be signaled TinyOS will handler this event and execute the corresponding code. On the other side as the commands, events usually are triggered by the lower layer and handled by upper layers.

To sum up we can see that TinyOS and nesC works together to provide an easy enviorment to build our application for sensors networks. Furthermore we will have components that connects to other components using interfaces. For each interface we will provide some commands (call functions) and we must implement the code for some events (timer fired, data receive, etc). The Figure 1.1 show us the TinyOS and nesC component model.

1.3 TOSSIM

TOSSIM (TinyOSSIMulator) simulates entire TinyOS applications. It is just a TinyOS library and it works by replacing components with simulation implementations. The level at which components are replaced is very flexible: for example, there is a simulation implementation of millisecond timers that replaces HilTimerMilliC. Similarly, TOSSIM can replace a packet-level communication component for packet-level simulation, or replace a low-level radio chip component for a more precise simulation of the code execution. Most of the real components contains a TOSSIM abstraction implementation to simulate the component.

TOSSIM works as a discrete event simulator. When it runs, it pulls events of the event queue (sorted by time) and executes them. Additionally, tasks are simulation events, so

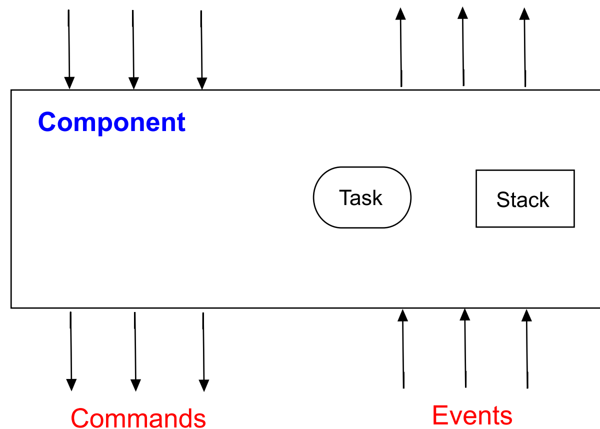


Figure 1.1: Component model

that posting a task causes it to run a short time in the future.

Sometimes it's important and very useful to debug the code. TinyOS and TOSSIM don't have their own debugger. ETH of Zurich has developed a plug-in for Eclipse named Yeti2 that allow to program TinyOS applications on Eclipse and also includes a debugger. On the other hand TOSSIM give us the possibility to print out some values on the standard output. Moreover we can configure and decided which messages we want to show to the output.

Although the choice of using the eclipse plug-in is very attractive, I will use debug statements providing by TOSSIM to show some important output of my applications (like packet information, battery information, routing information, error information, etc).

1.4 Our Workspace

It's possible to run TinyOS under any Linux-like, Mac OS or Windows. Furthermore there is a live-CD called XUbunTOS with the full operative system installed on it. Just launch it and you will have the full TinyOS running in your machine.

In our case, we're going to install TinyOS in a Ubuntu Linux machine. We can choose between install the version 1.x or 2.x, but TinyOS 1.x is not supported right now and is discouraged. Hence, we will use 2.1.0 version of the system.

Concerning to TOSSIM there are also two versions: 2.0.1 and 2.0.0. There are significances differences between both versions like how to specify the noise for the simulation. We will use the 2.0.1 version because it's the newest. Thus, the simulator will help us to check how the applications work and later if we see that the program works properly we can install it in a set of remote sensors nodes.

Processor	4Mhz 8 bits Amtel
Memory	4KB RAM, 512 flash
Radio	916MHz, 40Kbps, 35m range
Lifetime	Aprox: 2 weeks (full work)/1 year (low consumption)

Table 1.1: MICAz specifications

TinyOS runs in different kinds of chipset like CC2420 (used in micaz, telos family and imote2) or transceivers such as MICA family (MICAz, MICA2, MICA2dot), Telos family (Telosa and Telosb), TinyNode (serial port), eyesIFX-family... But TOSSIM only can simulate the behavior of MICAz motes, not the rest of the motes. Thus, from now we are going to focus only in the MICAz model. To give an idea of the resource constraints the Table 1.1 shows the specification of the mote.

1.5 Example of application

On the following lines we are going to introduce an example of a very easy application to see how TinyOS and nesC work. We're going to implement the "HelloWord" program. As I said before nesC is a component-oriented language programing so we have to think as if we're programing in a hardware description language.

To make any application we need two different types of files: module and configuration. For convention modules are named ended "xC.nc" and configuration with "xAppC.nc". In our example, we have two files called "HelloWorldC.nc" and "HelloWorldAppC.nc". Configuration are used to assemble other components together, connecting interfaces used by components to interfaces provided by other. Every application is described by a configuration that wires together the components inside. We can image that components are like blocks that we have to connect each other through interfaces. On the other hand, we also have the module file, that provides the implementation of one or more interface and uses interfaces from other modules. Modules are those who actually implement the functionality and do the work. As we can see interfaces is the mechanism to wire components. They have commands that are called by the module using the interface and events that are captured by the modules also using the interface. Thus, we have the schema showed in figure 1.2.

1.5.1 Configuration file (HelloWorldAppC.nc)

The configuration has two parts the configuration section and the implementation section.

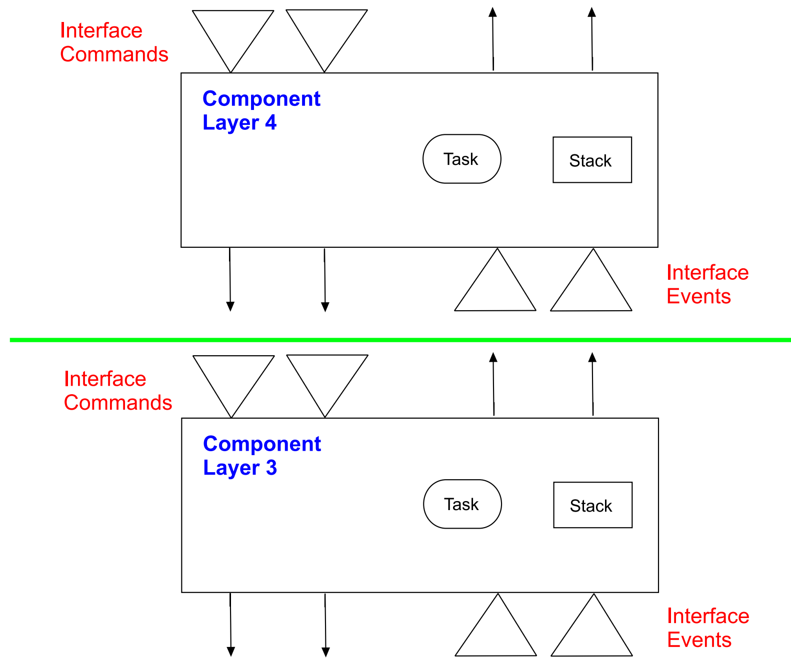


Figure 1.2: Module and its basic interfaces

Algorithm 1.1 Template of the configuration file

```
1 configuration HelloWorldAppC{
2 .....
3 }
4 implementation{
5 ....
6 }
```

In the configuration braces we can specify uses and provides interfaces as with a module. Because of helloWorld is an easy module application we don't need to use this.

Inside the implementation part, we have to define all of the components that we're going to use. In our example these are: HelloP, Boot, LedsC and SecondLedsC. The last two interfaces are different instances of the same interface. Thus, we can define many instance of the same interface as we want. The next step, is to wire interfaces used by modules to interfaces provided by others. For example, we will connect the interface provided by LedC with the interface uses by HelloC. Full code is written in algorithm 1.2 and Figure 1.3 is an image representing the latter.

Algorithm 1.2 HelloWorldAppC.nc Configuration file

```
1  configuration HelloWorldAppC {
2
3  }
4
5  implementation {
6      components HelloC, MainC, LedsC, SecondLedsC;
7
8      // USES -> PROVIDES
9      HelloC.Boot -> MainC.Boot;
10     HelloC.MyLeds -> LedsC;
11     HelloC.MySecondLeds -> SecondLedsC;
12 }
```

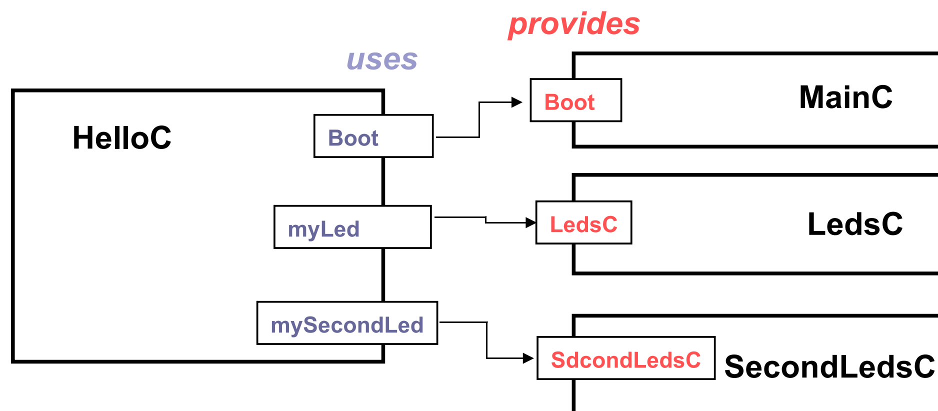


Figure 1.3: Configuration file

1.5.2 Module File (HelloWorldC.nc)

The module file is also organized in main parts:

Algorithm 1.3 Template of module file

```
1 module HelloWorldC {
2 ......
3 }
4 implementation {
5 ......
6 }
```

In the first part, we will declare the interfaces it provides and uses. In our case we are going to use: Boot and two instances of Leds named myLed and mySecondLed. In the second part, we can decide what the program is going to do depend on the events signaled. For example when the boot event signaled we will switch on the led. We must implement all the events for the uses interfaces. In other words, we have to capture and handle the events. For each interface we can see which events we must handle in the TinyOS documentation [1]. Furthermore during this process we can execute commands (with the reserved word call) provided by interfaces. This is consistent with the draw on figure 1.3. Here we present the whole code of the module:

Algorithm 1.4 HelloWorldC module file code

```
1  module HelloWorldC {
2      uses {
3          interface Boot;
4          interface Leds as MyLeds;
5          interface Leds as MySecondLeds;
6      }
7  }
8
9  implementation {
10     event void Boot.booted() {
11         call MyLeds.led0On();
12         call MySecondLeds.led0On();
13     }
14 }
```

As we can observe this program does the following: when the system is booted led1 and led2 switch on. Below is showed and intuitive draw showing this concept (red labes indicate that we must implement this event or command):

[1] http://www.tinyos.net/tinyos-2.x/doc/nesdoc/micaz/

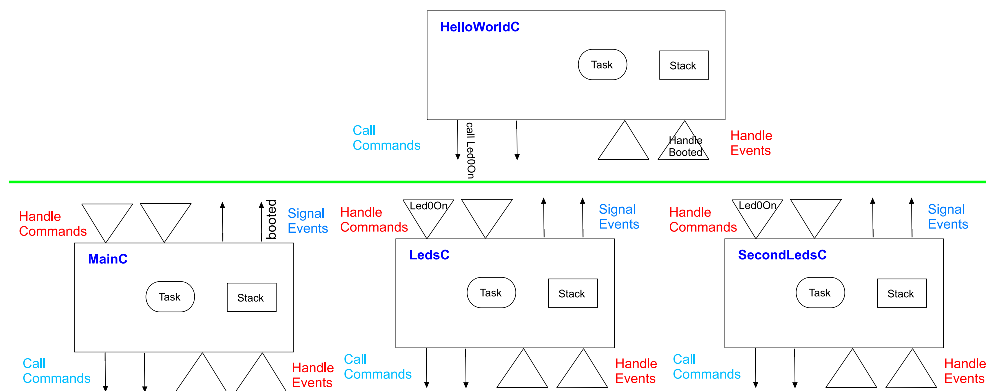


Figure 1.4: Components and their respective commands and events

1.6 Configuring TOSSIM

To run TOSSIM, first we must configure the simulation and specify a network topology. The latter means that we have to decided which are the connexions between the nodes. Thus, the behavior of the link depends on two elements: the radio and the enviorment (channel) where they are placed. The radio model is based on the CC2420 and more details about it is found in this page[2]. In addition TOSSIM simulates noise too but its aim is to provide high fidelity simulations rather than replicate the real enviorment.

We can specify the network topology either in terms of gain or in term of linked nodes. We will choose the first option and the way to said that node 'src' is connected with 'dest' is "gain src dest g". This statement defines the propagation gain 'g' when 'src' transmits to 'dest'. If we want to know more about this model just take a look of the web page at footnote 2.

To program this node connection statements, TOSSIM supports programing interfaces written in python and C++.

1.7 Security

Security is always an issue to take into account from the mainframes to small devices. In sensor network because of communication is performed via wireless (radio), any user can listen the information and also inject packet.

TinyOS 1.x has a module named TinySec that implements an abstraction layer of some cryptographics functions to make the communication more secure. With this se-

[2]http://docs.tinyos.net/index.php/TOSSIM

curity component we can run TOSSIM and check that the communication is ciphered. For TinyOS 2.x (that is actually the system that we are using) there is no secure layer implemented to simulate with TOSSIM. Due to TinyOS 1.x is currently not supported and discourage we will not use any cryptographics function to cipher our packages. Although if we don't want first to simulate the behavior of the network and just want to install the application in the nodes, motes with CC2420 transceiver has some in-line security features. This tutorial [3] explain how to enable some security options in our applications.

Concerning to my algorithms we are going to suppose that all nodes never have a malicious behavior neither in the network nor when they are running the formation protocol. In Section 7 we will study which are the security threats of the algorithms implemented.

[3] http://docs.tinyos.net/index.php/CC2420_Security_Tutorial

2 LEACH algorithm

Cluster algorithms can be split into two main categories: leader first approach and cluster first approach. In the leader first solution cluster head are elected based on certain metrics, and they agree on how to assign other nodes to different clusters. In cluster first approach all the sensor nodes first form clusters, and each cluster then elects its cluster head [20]. LEACH algorithm is inside leader first cluster head group.

2.1 Description

LEACH (low-energy adaptative clustering hierarchy) is a clustering-based routing protocol that uses randomized rotation of cluster heads to evenly distribute the energy load among the sensors in network [21]. This algorithm is a self-organized, adaptative clustering protocol that the nodes organizes themselves into a local clusters, with one node as a cluster-head. A precondition of the algorithm if that each sensor can reach the sink, so it can be elected with the guarantee that it is going to rout the data toward the sink.

Once the cluster is build, each CH makes a schedule that broadcast to all of its children. After this each children will transmit in its corresponding slot whitin the schedule. The CH have wait until all its nodes had sent their data and then the cluster will transmit all the data aggregation to the sink. We have to remark the fact that the CH is not always the same node, this role is rotated periodically among all nodes.

With the above model we can save up energy, because is cheaper to send data to my CH instead of transmitting packets always to the base station (it will be farther). For the cluster-head also is less energy to transmit all the data aggregation to the base station than sending packet per packet (because we have to send less packets and the information can be compressed). Furthermore the CH is always changing thereby allowing to balance the load between the nodes.

In addition during the process, a TDMA schedule for the child nodes is created and each sensor will only transmit in its corresponding slot, so in the rest of the schedule slots they can be sleeping and save energy. If the nodes are completely synchronized, it is possible to turn off the radio until the next time of transmitting in the TDMA schedule starts. If can not do this accurate synchronization we can use protocols like LPL (Low Power Listening) in order to keep most of the time the node sleeping and do periodic checks to know if the radio has to switch on again. Finally another good feature of

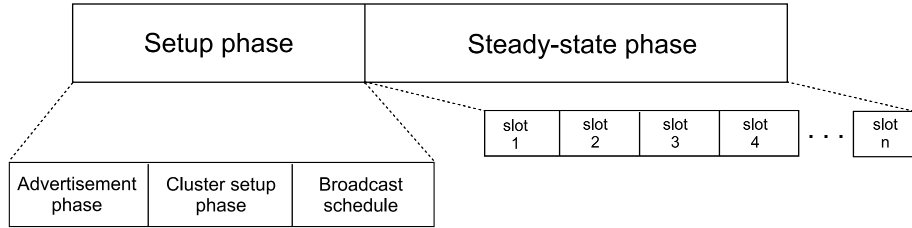


Figure 2.1: One round LEACH algorithm phases

the algorithm is that converge in a fixed number of iterations regardless the number of nodes deployed.

We also must say that LEACH perform one-hop intra (communication between the node and elected CH) and inter (CH communication with the base station) cluster topology where nodes can send packages directly to the CH and thereafter to the sink (hasn't got peer-to-peer). Because of this one-hop topology nature, this kind of cluster formation is not suitable for network deployed in a large regions (otherwise CH maybe can't reach the base station due to is too far away from it).

On the other hand a big drawback of this protocol is that it can't guarantee that each non-clusterhead node belongs to a cluster due to the collisions in the advertisement and the join phase. Nevertheless it can guarantee that nodes belong to at most one cluster [14].

2.2 Protocol Specification

LEACH forms clusters by using a distributed algorithm, where nodes make autonomous decisions without any centralized control. The algorithm works in rounds, when each round begins with the setup phase (when the cluster is organized), followed by a steady-state phase (when data transfer to the sink). More specifically we can divide the setup phase into three more steps: advertisement phase, cluster setup phase and schedule creation phase. Figure 2.1 shows the different phases during the algorithm.

2.2.1 Phase 1: Setup Phase

As we said before this phase is divided in three parts:

1. **Advertisement phase:** each node decided based on a formula whether or not to become a CH for the current round. The formula that we will uses [7] to decide the latter is:

$$T(i) = \begin{cases} \frac{p}{1-p*(r*mod*(1/p))} & if\ i \epsilon G \\ 0 & otherwise \end{cases}$$

Where variable p allow us to decide the desired percentage of CH node in the sensor population, r is the current round number and G is the set of nodes that have not been CHs in the last 1/p rounds. Now each node has to choose a random number "T" between 0 and 1. If the random number is less than the calculate threshold, this node will be a good candidate. After this, each node that is elected as a CH will send a broadcast message advertising all nodes. In the next steps each non-cluster-head node decides the cluster to which it will belong for this round depending on the signal strength or the distance.

2. **Setup phase:** each node has decided to which cluster belongs. The node will send a message to the CH informing that it will be a member of that cluster. The decision is made based on the distance between the CH and the respective node. We will choose the nearest CH.

3. **Schedule creation:** CH receives all messages from nodes that would like to be in its cluster. Once the CH know the number of children, it can create a TDMA schedule, when only one node will transmit in each slot. Then the schedule is broadcasted to the nodes members of the cluster.

2.2.2 Phase 2: Steady-State Phase

Phase 2 is the last stage, here each node will send its data to the CH during its allocate time in TDMA schedule. When all the data has been received (data aggregation), the CH will compress the information and it will transmit this to the base station.

When the sink received all the data aggregation from the CH, it can deliver a message to all nodes to advice that new round begins. This allow us to keep all nodes synchronized at the beginning of the next round, because a new round doesn't start until the sink has received all the data from all CH. Thereafter the algorithm start again from phase 1, choosing different CH from the previous rounds.

2.3 Example

We are going to take as a reference for the example the grid topology with 12 nodes (Figure 2.2). When a new round starts, all nodes begin with the phase 1. Sensors calculate the T(i) value (that is $T(i) = 0.2$) and each node will generate a random number. In this round the only nodes that have had a number less than 0.2 are node 8 (0.1) and node 2 (0.1). Thus, those node will became a CH and they will send an announcement message telling all nodes that they are CH. Moreover base station will be listening the announcements and it will store how many CH are in the network to use it in further actions.

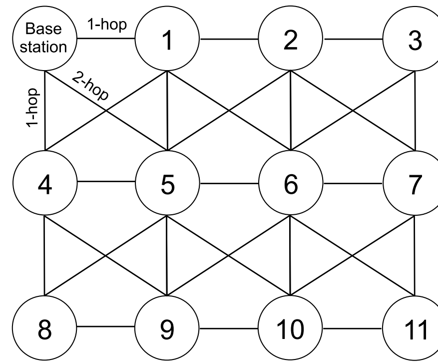


Figure 2.2: Grid topology with 12 nodes

Then each node received the broadcast messages from CH and they will choose the better CH for him. That decision is based on certain parameters such as distance, strength signal or battery level. In this example we are going to take the distance as a critical factor to choose between the CH candidates. Thus, for nodes 6, 1, 3 and 7 the best choice is node 2, while for the rest sensors (10, 9, 4 and 5) the best options is mote 8. Actually for node 5 and more motes there is the same distance from both CH, so it will associate to the first node that received the announcement packet. When they pick up their best choice, they will transmit an associative message to the elected CH.

Once the CH had received all the associate packets they know how many children they have and can build the TDMA schedule. In that timetable only one node can send at the same time and all the nodes have mandatory a slot to send a message to the leader. Then CH node will broadcast the schedule created. The TDMA that broadcast node 2 is $\{6,1,3,7\}$ and node 8 is $\{10,9,4,5\}$

At this point phase 2 starts. While nodes are sending messages in its corresponding slot to the CH, this will aggregate all the data received from different children. Node 6 will be the first that transmit a packet to node 6 and at the same time node 10 will send a message to 8 (but different CH). The other motes will have the same behavior, they wait until its turn and when it arrives they will transmit. Once all nodes had sent their messages to the CH, this will compact all the data aggregation and then it will send to the base station (they will transmit only one message). When sink receive all the data from the CH, it can give the order to start the next round.

Now the round 2 starts and there will be new CH announcements. Remember that the previous CH's can't be elected until all the rest nodes were CH.

3 Distributed cluster (Clique) algorithm

As we said in the chapter before, there are two groups of clustering algorithms: leader first and cluster first. Clique algorithm belongs to cluster first set. That means that sensors first will form clusters, and then will choose their cluster head. All nodes in the same cluster must agree with the elected cluster head. In other words all nodes have to be a consistent with the view of its cluster (clique) and its cluster head (CH).

3.1 Description

Clique is a cluster formation protocol that exchanging information with 1-hop neighbors sensors nodes are divided into mutually disjoints cluster (cliques). The protocol aims to divide the sensor network into multiples small groups and guarantees that all the nodes in each clique agree on the same clique membership. The protocol has the following properties:

- It is full distributed. Each node computes its clique only using information from its 1-hop neighbors.
- It is guarantee to terminate.
- After protocol terminates, all nodes are divided into mutually disjoint clique. They have consistent view on their clique membership.

The original algorithm [20] assumes that each node knows its 1-hop neighbors and they have and unique ID.

3.2 Protocol Specification

The protocol is divided in four steps:

1. Each node exchanges its neighbor list with its neighbors, and computes its local maximum clique.
2. Each node exchanges its local maximum clique with its neighbors, and update its maximum clique according to its neighbor nodes local maximum clique.

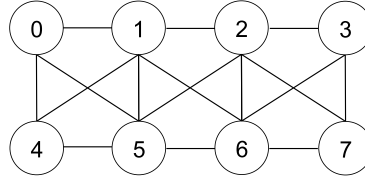


Figure 3.1: Grid network with 8 nodes

3. Each node exchanges the update clique with its neighbors and derive its final clique.

4. Each node exchanges the final clique with its neighbors and check if they are consistency.

3.3 Implementation

3.3.1 Step 1: Local Maximum Clique

First of all we will calculate which are our neighbor and will store it in a matrix. In a network that spreads randomly when the sensors turn on they have no idea about which are their neighbor. Hence we have to find a mechanism to figure out this problem. Section 6.1 explains how to resolve it.

In this example we are going to focus in sensor number 1, but the same procedure can be applied to the remaining nodes. The neigborhood obtained for sensor 1 is described at Table 3.1.

Once we have our list of neighbors, we can start to exchange data with them. The first information that we will send is our neighbor list to all of them. After that we will begin with the calculation of the local maximum clique. That means, we are going to choose the nodes that have more common neighbors with us and those neighbors will be the local maximum clique. In the paper [20], there is an heuristic algorithm to find the local maximum clique.

In the following paragraphs, we will show and example to know how does it work. Imagine that we have the network of figure 3.1 and its respective neighbor matrix (showed in table 3.1).

Now we are going to calculate the local maximum clique of node 1. We will use three sets to allocate some data during the algorithm:

- C_1: local maximum clique final set of nodes.
- L_i : set of node i neighbors.
- S_1: set of nodes to be chosen for the next iteration.

Node	0	1	2	3	4	5	6	7
0	**1**	**4**	**5**					
1	**0**	**2**	**4**	**5**	**6**			
2	**1**	**3**	**5**	**6**	**7**			
3								
4	**0**	**1**	**5**					
5	**0**	**1**	**2**	**4**	**6**			
6	**1**	**2**	**3**	**5**	**7**			
7								

Table 3.1: Node 1 Neighbor's matrix

At the beginning of the algorithm the previous structures are initialized like this: $C_1 = \{1\}$ (final clique contains itself), $S_1 = \{0, 2, 4, 5, 6\}$ (its neighbors list) and L_i (node i neighbors list). In the first step of the algorithm we have to find $k \epsilon S_1$with maximum $\mid L_1 \cap L_k \mid$. Looking at the neighbor matrix we notice that $L_1 \cap L_5 = \{0, 2, 4, 6\}$ is the biggest set of common neighbors. So we deleted this node from the $S_1 = \{0, 2, 4, 6\}$ and add it to the $C_1 = \{1, 5\}$. Now we check if the node elected (in this case node 5) is reachable from nodes in set S_1. In this case all nodes in $S_1$are connected with node 5 (we know this just looking at the neighbor matrix in table 3.1). At this point we arrive at the end of the first iteration. Node 1 continues repeating the process until $S_1$is empty.

In the second iteration, we choose $L_1 \cap L_0 = \{4, 5\}$ as a maximum set of common neighbors between node 1 and any node in S_1. Then we add the node to $C_1 = \{1, 5, 0\}$ and delete it from S_1. Moreover we check if the elected node 0 is linked with $S_1 = \{2, 4, 6\}$. Now we notice that node 0 is not connected with 2 and 6 and we proceed to eliminate these nodes. After this we have $S_1 = \{4\}$. Because of $S_1$is not empty we go on to next iteration.

The third iteration it seems to be the last. We have only one node to choose in S_1. We pick them and look which are the common neighbors $L_1 \cap L_4 = \{0, 5\}$. Later we modify $S_1 = \{\}$ and $C_1 = \{1, 5, 0, 4\}$. Now $S_1$is empty and the algorithm ends obtaining the local maximum clique that is the $C_1 = \{1, 5, 0, 4\}$.

For each node in the network we have to run the heuristic algorithm until they find its local maximum clique. The pseudocode for it and some more information is found in [20].

3.3.2 Step 2: Ordering and Updating Maximum Clique

In this step we will exchange the local maximum clique (C^1) calculated at point 3.3.1 with the neighbors. We can manage this either broadcasting or sending to one-hop neighbor and then it will retransmit to the next neighbor. The advantages and disad-

Node	0	1	2	3	4	5	6	7
0	**0**	**1**	**4**	**5**				
1	**1**	**5**	**0**	**4**				
2	**2**	**6**	**1**	**5**				
3								
4	**4**	**0**	**1**	**5**				
5	**5**	**1**	**0**	**4**				
6	**6**	**2**	**1**	**5**				
7								

Table 3.2: After step 1: node 1 local maximum clique (C_1^1)

vantages of this is discussed at section 6.1. Once we have received all the local maximum clique from my neighbors we are going to order all of clique to check if there is any $\mathrm{C}_{\mathrm{i}}^1$ which is better than C_j^1. We can say that $\mathrm{C}_i^1 > \mathrm{C}_j^1$ if:

- Both cliques C_j^1 and C_i^1 mandatory have to contain node k.
- If $\mid C_i^1 \mid > \mid C_j^1 \mid$, then $\mathrm{C}_i^1 > \mathrm{C}_j^1$.
- If $\mid C_i^1 \mid = \mid C_j^1 \mid$, we compare the index. If i > j then $\mathrm{C}_i^1 > \mathrm{C}_j^1$.

Let us to illustrate the latter with an example. For the network in image 3.1, we have the local maximum clique of node 1 on table 3.2. As we have said before nodes exchanges their local maximum clique with its neighbors.

Now we are going to order the cliques received to know which is the best clique for node 1 (C_1^2). First of all, we check if all cliques (C_{j}^1) in the table contain node 1. If it isn't we can't compare these cliques and we have to drop the clique (C_{j}^1). In this case all cliques (0,2,3,4,5,6) have node 1 in its list of nodes. So, we don't delete any clique. After this, we compare the length of the cliques and order them from the largest to the shortest. Here we can notice that all of our cliques have the same length. To break this tie we will choose the clique of its bigger neighbor ID. The ordered list of node 1's cliques is: $C_6 > C_5 > C_4 > C_2 > C_0$ and the $C_1^2 = \{6, 2, 1, 5\}$.

3.3.3 Step 3: Obtaining Final Clique

Each node broadcast its update clique C_i^2 to their neighbors. For every node *j* in C_i^2, node *i* check if it's included in *j*'s clique C_j^2. If not, node *i* removes *j* from its clique C_j^2. After this step, each node *i* has its final clique C_i^3.

For our example in figure 3.1 the next table show as the result after step 2:

For node 1 example the clique is $C_1^2 = \{6, 2, 1, 5\}$. If we check $C_6^2 = \{7, 2, 3, 6\}$ we can notice that sensor 1 is not in the list. Thus we remove node 6 from our final clique.

Node	0	1	2	3	4	5	6	7
0	**5**	**1**	**0**	**4**				
1	**6**	**2**	**1**	**5**				
2	**7**	**2**	**3**	**6**				
3								
4	**5**	**1**	**0**	**4**				
5	**6**	**2**	**1**	**5**				
6	**7**	**2**	**3**	**6**				
7								

Table 3.3: After step 2: node 1 updating maximum clique (C_1^2)

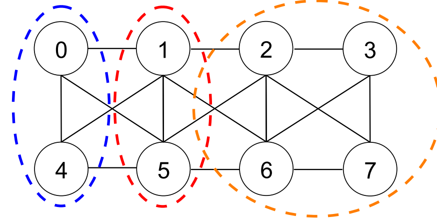


Figure 3.2: Final cliques for grid network with 8 nodes

The same occurs for node 2, which the clique is $C_2^2 = \{7, 2, 3, 6\}$ and again node 1 is not included, consequently we have to drop out node 2 from our list. The next sensor is id five and its clique is $C_5^2 = \{5, 1, 0, 4\}$. I we check out the set we find out node 1 is inside, so we keep this node in the list. At the end the final clique is: $C_1^3 = \{1, 5\}$.

3.3.4 Step 4: Checking Clique Agreement

After step 3, we can guarantee the clique agreement. Now each node just broadcast their final clique (C_i^3). Then nodes verifies the clique agreement, that is, node i verifies for all $j \epsilon C_i^3$, whether $C_i^3 = C_j^3$ holds. In the Figure 3.2 we can see the final cliques obtained for every sensor at the end of the protocol.

4 Distributed bounded-distance multi-clusterhead algorithm

Bounded-distance multi-clusterhead formation algorithm (Spohn and Garcia-Luna-Aceves [19]) is a distributed clustering using (k,r)-dominating sets. Any node is said to be (k,r)-dominated if node i has at least k neighbors with distance r in D. This multi-clusterhead protocol allow the nodes to have several CH (redundancy) in order to have fault-tolerance for the applications. If we go on with the two differents approach for clustering algorithm (leader-first and cluster-first), this algorithm will be included in the leader-first group due to at the beginning nodes try to find out which are its best CH and then join them. In this chapter we will see which are the goals of have a cluster (or a multi-cluster) and how to perform them.

4.1 Description

In the WSN's field, a cluster is a group of linked sensors. This kind of structures is very useful in WSN's, because it can helps to achieve an increase of timelive, balance the load in the network and good scalability. Thus, clustering is the problem of building hierarchy among nodes (clusters) [9]. Each cluster has one node that represents it, that is the cluster-head (CH). Thereby the network can be abstracted such just the connection between cluster-heads.

To achieve these clusters usually we have first to calculate the dominating set (DS) of the network. The domination problem seeks to determine the minimum numbers of nodes D (called dominating nodes or cluster heads) such that any node *i* not in D is adjacent to at least one node in D [19]. This problem is NP-complete.

For the (k,r)-Dominating set problem, *r* defines the maximum distance from nodes to their cluster-heads and *k* the minimum numbers of dominating sets per node. We can notice that with a *k* greater than one we have redundancy that we can use it to build fault-tolerant applications.

4.2 Protocol Specification

The Spohn algorithm has two main phases. The first is called election phase and here each node elects *k* nodes with small ID (also including itself) with distance *r*. This

elected nodes are not CH yet, they are only candidates. Later, the second and the last stage starts. During this, cluster heads are finally elected and the rest of nodes have to associate to their dominating nodes (CH). It must have k nodes in every node's r-hop neighborhood, otherwise the domination set k is not satisfied. That is in outline how the algorithm works. Now we are going to see the details of each phase.

4.2.1 Phase one

Before the algorithm starts, this assumes that nodes have an unique ID and each node knows who are their neighbors. How to figure out this is discussed in Section 6.1. So we are going to omit this first step and we will focus in algorithm itself.

The whole program works in rounds and specifically this stage takes r rounds to finish. Once we know which are my neighbors, we can make a list with k smallest neighbors ID nodes. Then they will send the list to their neighbours. Here round 1 finishes and we can notice that at this point we have the k-smallest ID within r distance. This process is repeated as many times as r. At the end (round r) we will have in D_i^r the final set of k smallest ID nodes within distance r.

After that each node looks at this final list and they will change its status based on:

- If node is elected by itself its status will become to *pending dominated*.
- If node have fewer r-hop neighbours that the required multiple domination parameter k, this node is not satisfiable and must become dominating. Thus, this status will change to *dominating* and it has to send a NA message too.
- Otherwise it change the status to *dominated*.

As we can see there are several node status. The meaning of them are:

- *Dominating*: the node is a cluster-head.
- *Pending* dominating: the node may become a CH.
- *Dominated*: the node has at least k cluster-heads within distance r.
- *Gateway*: in addition to being dominated, the node connects other nodes to their CH.

4.2.2 Phase two

In summary during the phase two some nodes elected in phase 1 will become CH. The rest of the nodes are affiliated to their corresponding cluster-heads. In this phase we will use some messages to transmit information to other nodes. Those are:

- Local advertisement (LA): a message with the list of elected node by the node i and their respective next-hop of that elected node.
- Neighborhood advertisement (NA): a message advertising a CH.
- Notification: a message send to notify a node that must become a CH.
- Join: a message associate to a CH.

First of all *dominated* nodes send only to their one-hop neighbours a LA message. Any *dominated* node i that receives the LA packet will do:

1. If node i is listed in the list of LA message, node i changes it status to *dominating* and it will send a NA message announcement itself as a CH. This is accomplished by broadcasting NA message using restricted blind-flooding with the TTL field set equal to r.
2. If node i is not listed in the list of LA message received but is listed as a next-hop of any advertised node, then node i changes its status to *gateway*.
3. For any advertised node a that is not among the nodes elected by node i (is not in D'_i) and the node is in the path to a, it must send a notification message to a.

Once all local advertisement messages have been received, nodes that have to send a notification message to some mote (because of the previous point 3) it is time to do it. With this process any node that receives a notification package must become CH. After that, sensors that have pending NA messages to transmit (due to the point 1 above or phase one) it will send them.

NA messages are delivered using blind-flooding that means all nodes whitin r-hop distance will receive the packet. For each NA message that we listen we will validated that node. This is the same as saying, for any node i and for all $n \epsilon D'_i$, node n is deemed validated only upon the reception of the respective NA message advertising node n; otherwise the node n is not yet validated [19].

Now we will check if the agreement has reached. We will wait a period of time that is defined as the minimum time required for reaching an agreement in phase two. After this period if node i is pending dominating and it does not have enough validated entries in D'_i, then node i changes status to *dominating*, and send a NA message. Otherwise any non-dominating node i sends a join message to k nodes from D'_i [19]. Like notification messages, join packet also assigns *gateway* status the node when the message is being routed. That is, if the receiver node is not the target, it will change its status to *gateway* and will relay the message. How message are retransmitted is discussed in section 6.2.

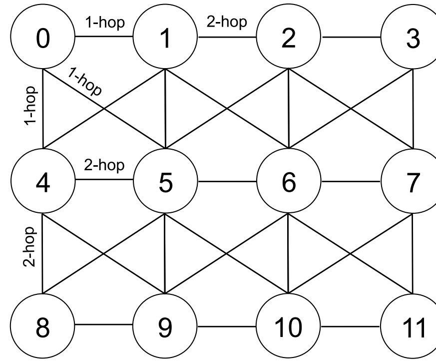


Figure 4.1: Grid topology network with 12 nodes

4.3 Example

We are going to take as the example the grid topology with 12 nodes. Our *k* and *r* values will be 2 and 1 respectively. The Figure 4.1 shows the corresponding network. This grid topology is not the same as the examples in the previous chapters. Notice that now the one-hop neighbours is a square radius of one.

The Spohn algorithm starts with the phase one and this will take *r* rounds. In the first round nodes exchange its list *k* lowest IDs with its neighbours. Because of it is the first one, the list of lowest IDs only contains the node itself. The first step is to take that list from the *MatrixD* matrix as we can see in the Figure 4.1. Later, all nodes build a packet like *messageList* (look Figure 4.1) and exchange this list with their 1-hop neighbours. In the second step, each *messageList* received packet is stored in a new matrix called *messageMatrix*.

In the third step, once all packets have been received, nodes figure out another time the *k* lowest IDs from all list received (remember that k is equal to 2, thus we have to choose the 2-lowest IDs). The result is store in the *matrixD* matrix (step 3 of Figure 4.2). Because of in this example *r* is equal to 1, we don't start a new round and phase one ends.

However in the case that we have more rounds we will start again with the step 1 choosing the *k* members from *matrixD*, building the *messageList* packet and sending it. Then we will follow with the step 2 copying all the data received from the *messageList* to the *messageMatrix* and after this, in the last step, we will choose the k-lowest IDs. We will repeat the loop Figure 4.2 *r* times. The following draw (Figure 4.2) can help us to understand the process and which are the fields of each messages.

At the end of the previous algorithm, sensors have stored in *MatrixD* the list of the 2 lowest IDs between all 1-hop nodes. Table 4.1 show us the final values for the nodes.

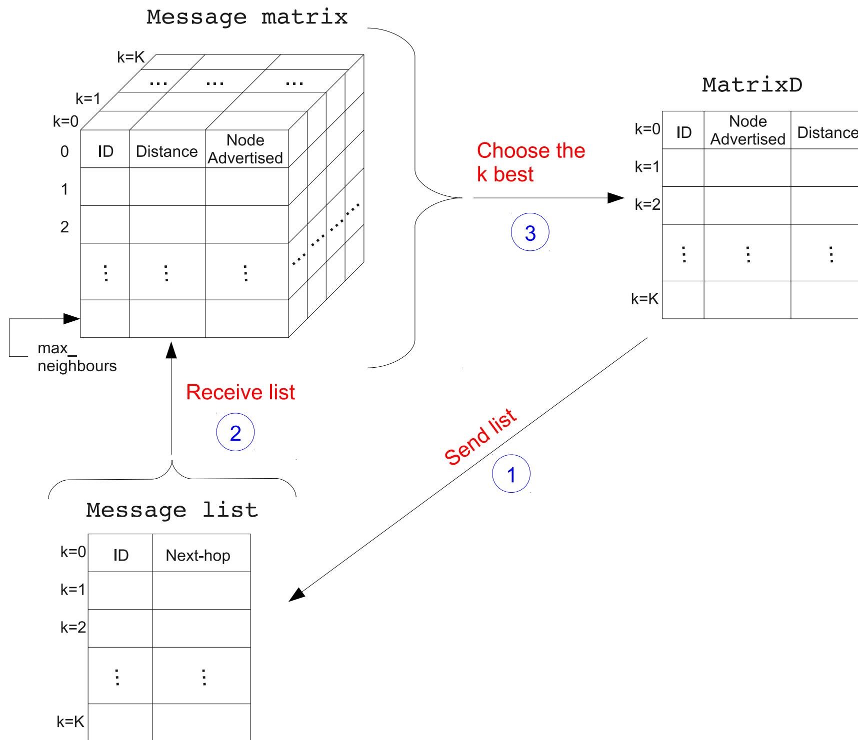


Figure 4.2: Spohn data structures and data flow

	MatrixD={{Id,Node Adv,Dist},...}
Node0	{{0,0,0},{1,1,1}}
Node1	{{0,0,1},{1,1,0}}
Node2	{{1,1,1},{2,2,0}}
Node3	{{2,2,1},{3,3,0}}
Node4	{{0,0,1},{1,1,1}}
Node5	{{0,0,0},{1,1,1}}

	MatrixD={{Id,Node Adv,Dist},...}
Node6	{{1,1,1},{2,2,1}}
Node7	{{2,2,1},{3,3,1}}
Node8	{{4,4,1},{5,5,1}}
Node9	{{4,4,1},{5,5,1}}
Node10	{{5,5,1},{6,6,1}}
Node11	{{6,6,1},{7,7,1}}

Table 4.1: *MatrixD* values after phase 1

Now nodes change its status as follow: node 0, 1, 2 and 3 are self-elected nodes, so their status will be *pending dominating*. The rest of sensors have the status set to *dominated*. At this point phase one of Spohn algorithm finishes.

First of all in the phase 2 all *dominated* nodes have to send a LA message to their one-hop neighbor. Nodes 4, 5, 6 and 7 will receive that message from nodes 8,9,10 and 11, thereby nodes 4,5,6 and 7 will become a *dominating* node and later they will send a NA message. Sensors 0,1,2 and 3 because they are *pending dominated* nodes that don't change their status to *dominating* and they are still *pending*. Any node has to send a

notification message due to all advertised nodes are among the nodes elected (*matrixD*).

All nodes that have NA message to send, it is time to do it. Nodes 4,5,6 and 7 will transmit the NA packet to their neighbours. Each node that received the message will add this mote to the *matrixD* and also will validate the node. After all messages have been processed the *matrixD* of sensors are the values on Table 4.2.

	MatrixD={{Id,Node Adv,Dist},...}		MatrixD={{Id,Node Adv,Dist},...}
Node0	{{4,4,1},{5,5,1}}	Node6	{{-,-,-},{-,-,-}}
Node1	{{4,4,1},{5,5,1}}	Node7	{{-,-,-},{-,-,-}}
Node2	{{5,5,1},{6,6,1}}	Node8	{{4,4,1},{5,5,1}}
Node3	{{6,6,1},{7,7,1}}	Node9	{{4,4,1},{5,5,1}}
Node4	{{-,-,-},{-,-,-}}	Node10	{{5,5,1},{6,6,1}}
Node5	{{-,-,-},{-,-,-}}	Node11	{{6,6,1},{7,7,1}}

Table 4.2: *MatrixD* values after receiving the NA message

The next step is to check the agreement. Because all *pending dominating* have enough validated entries in *matrixD* they will change their status to *dominated*. After that, all nodes send a join message to their elected nodes. We can see the final network and which are the dominating and dominated nodes at Figure 4.3 .

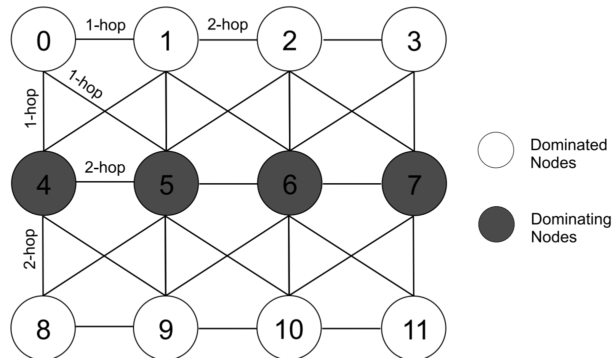


Figure 4.3: Dominated and dominating nodes after Spohn algorithm

5 New Distributed multi-clusterhead algorithm

In the last algorithm there are some topologies where the Spohn-Garcia protocol chooses too many dominating nodes (cluster heads). Our goal now is to provide a good performance for all topologies (not the optimal for all cases, but always a good solution). The protocol also assures that each node will have k cluster heads within r hops. Furthermore this new implementation will save all the possible paths from the node to all its neighbors in order to support fault-tolerance if a link or path break-down.

5.1 Description

Distributed bounded-distance multi-clusterhead algorithm (see Chapter 4) usually calculates the optimal number the cluster. However there are topologies such a chain topologies (Figure 5.1) where the performance of this protocol is not very good. In the case of the latter network, the number of CH chooses by Spohn-Garcia are {1,2,3,4,5,6,7,8}, but in fact the best solution is to elect as a CH nodes {0,2,5,8}. To solve bad achievements we propose a new algorithm, that has a good fulfillment in all cases, but it's not always the optimal result.

In the new protocol a node can adopt three possible states: *slave*, *head* or *escaping*. Now, the idea is that each node picks up some node to be their CH. Then, could be that a node that is elected to be a CH (so its state is *head*) can have within its r-hop more than k heads nodes. In that case, this node will try to escape and become a normal node (*slave*). Thus, a node will inform their neighbor that it's trying to escape and if all sensors allow him to escape (in order words, any sensor doesn't need him as CH because there are others to fulfill its coverage) it will convert in *slave* mote. The procedure is repeated until the network converges to a state where all nodes states don't change anymore (any head node try to escape).

Another good feature is the fact that the algorithm can be launched in inconsistency

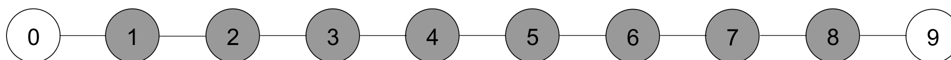


Figure 5.1: Chain network and CH elected by Spohn-Garcia

states. In Spohn-Garcia algorithm to run the network it is mandatory to know which are our neighbors and then chooses the *k*-smallest. In our new implementation is not necessary to learn this information (the protocol can be launched without have learnt our neighborhood before).

A drawback is that the protocol has to send many messages that be don't know beforehand until the network converge (it doesn't converge in fixed known rounds).

In addition, our algorithm supplies the full path from one node to all its neighbors. This can be used for faul-tolerant applicantions and it gives us the possibility to rout the information through several paths depends on some condition. However if we want this new feature, the number of packets sent and received will increase a lot in order to maintain the full tree (all possible path from the main node to the others). TinyOS doesn't support a big payload in its messages so we have to use some compression techniques to reduce the size of the message as well as a more elaborated mechanism to transmit the tree between our neighborhood (see Section 6.6).

5.2 Protocol Specification

The protocol works in rounds. Each round is divided in three steps:

1. Phase one. This phase will determine our state, generate a random number to escape and calculate the set of nodes to join.

2. Phase two: send join message to all members in the join list. If node get a join message it will become cluster head.

3. Phase three: if a node has modified its state, it has to send a message to their neighborhood advertising them. The nodes will update the status of their neighbors.

These tree stages will looped indefinitely until the network converge to a stable state.

The phase where all the hard work is done is the first one. There first of all, each node updates it set of head nodes (they know that information because in step three all nodes excahnge its status) and save them in a join list. In the case that we haven't got enough head nodes to fulfill the coverage, we can pick up another mote that is not CH but it's in our neighborhood. Then CHs nodes which have more than *k* head in its list will try to escape from being a CH and become a *slave*. This is done by choosing a random number, so every of the previous nodes will have the chance to abdicate, but all them will not do at the same time. Nodes that have the opportunity to escape will change its state to *escaping*.

Here phase two starts. Each node sends a join message to its elected join nodes (calculated at point one). When a node receives a join message if he is not trying to escape

it will become a *head*. However if a node is trying to escape it will maintain its status to *escaping*.

In phase three all nodes will transmit its state. When a node receives node with state equal to head, it will update its list of head nodes within its neighborhood (if it hasn't got it yet). Nevertheless if it receives a message from a node with the escaping state the node will checks its coverage. If it has enough head nodes to fulfill the coverage, it will delete the node from its head list (allowing that node to escape). However if the mote hasn't got enough head, it will not let the node to escape. That means in following rounds it will get a join message.

After the description of the protocol a question can arise, how can a node doesn't let another to escape if when the status is escaping the nodes don't ignore join messages? The solution is because there is a pseudostate called *hoping* that takes one round after the *escaping* state when if any node send a join message to a sensor it will become cluster *head*. If during this hoping state a node doesn't obtain any join message it will convert to *slave*.

5.3 Example

Let's take the chain topology at Figure 5.1 to see how does the protocol works and to compare with Spohn-Garcia algorithm. The parameters are $k = 1$ and $r = 1$.

At the beginning nodes don't know anything about its neighbors, so all become *heads*. Now, because they have modified its state, sensors transmit a message informing the others that they are head.

At this point phase one starts. Each node updates their list of head nodes received before. After that, every sensor realizes that it has more head that the needed to fulfill its coverage (see Table 5.1). and because they are heads node select a random number for attempting to escape and become a slave mote. The arbitrary numbers and more information of this example are showed in Table 5.1.

Node	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
State	head	head	head	head	head	escp	head	head	head	head
Join set	{1}	{0,2}	{1,3}	{2,4}	{3,5}	{4,6}	{5,7}	{6,8}	{7.,9}	{8}
Random	3	10	5	2	1	0	6	11	7	12

Table 5.1: Nodes information in round 0

As we can observe, the first mote that it has a chance to escape is number 5 (internally we have another timer that increases from 0 till a defined constant and give the possibility to all heads to abdicate).

In the second phase, nodes send to their heads a join message. In the Table 5.1 we can

see the list of join messages that we are going to send. When a node receives a join it will convert into a head mote, except the node which is trying to escape (which its state is equal to *escape*). The Table 5.1 will show which are the states after the join messages have been received.

In the third phase nodes deliver a packet telling to their neighbors which is their update state after received a join message. At this moment when nodes 4 and 6 receive from node 5 the state escaping, they will check if they have enough nodes to accomplish the *k*-cluster head whitin *r*-hop distance. In this case nodes 4 and 6 have more heads in their list to fulfill the coverage (such as 3 and 7 respectively), so they will allow node 5 to escape by deleting it from their list of head nodes (that entails that these nodes will not send a join message any more to node 5).

At this time, a new round starts again. This is specially important for node 5 due to it is now in a pseudostate named *hoping* and if during this round anyone send a join message to him it will convert from hoping to slave.

The first step in this new round is phase one, which all nodes updates their list of head nodes for later send a message to them. Furthermore if the internal timer for escaping heads has reached any node, it will have the chance to abdicate. Table 5.2 summarizes all the important nodes information.

Node	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
State	head	head	head	head	escp	hop	head	head	head	head
Join	{1}	{0,2}	{1,3}	{2,4}	{3}	{4,6}	{7}	{6,8}	{7,9}	{8}
Rand	3	10	5	2	1	0	6	11	7	12

Table 5.2: Nodes information in round 1

In phase two, nodes will send join messages to their elected heads. In the case of sensor 4, because its state is *escaping* when it receives the join message from node 3 and 5 it will not become a head node. The others, when they get the packet with their Id in the message data field, it will convert to *head*. In addition, as we can see, any node is going to send a join message to node 5. Thus, node 5 will be finally a *slave* node due to anyone has requested it in this round.

At the beginning of phase three all nodes exchange their state. Nodes 3 and 5 receives from node 4 that their new status is *escaping*. As a consequence of this, they check if they more or equal to *k* head nodes in their list. Because both nodes (3 and 5) have to elements in their list and it only necessary one head per node, they allow node 4 to escape by deleting it from its head record.

Now a new round is going to start and we can observe all the necessary information in Table 5.3.

Again every node will update their heads nodes list, for further send a join message

Node	0	1	2	3	4	5	6	7	8	9
State	head	head	head	escp	hop	slave	head	head	head	head
Join	{1}	{0,2}	{1,3}	{2}	{3}	{6}	{7}	{6,8}	{7,9}	{8}
Rand	3	10	5	2	1	-	6	11	7	12

Table 5.3: Node information in round 2

to them. Because the internal timer for escaping nodes is equal to the random number of mote 3, this sensor will attempt to escape and become a slave.

In the next phase, sensors will send their corresponding join messages to their elected heads. As we can notice sensor 4 which is in the pseudostate *hoping*, will not receive any message from its neighbors. Thus at the end of this round it will be a *slave* node. Moreover number 3 will get a join message from two but because of it is escaping it will ignore the message and don't become in head. The rest of motes that acquire join message will be set as a *head*.

At the third stage nodes exchange its new states. Node 3 will get that sensor 2 is a escaping node (trying to abdicate as a head node), but if it checks its coverage it hasn't got enough heads to fulfill the requirements (*k* heads). Thereby node 4 doesn't delete three from its list of heads and consequently in the next mote 3 will get a join message. On the contrary, in the case of number 2 it has enough heads in its list, so it will delete node 3 from the record. Here we find a curious situation, because mote 2 allow node 3 to escape but node 3 not. The results is that if all nodes are not agree with the escaping situation the sensor will not escape.

Round number 2 is finish and now round three begins. All the important data for the next steps is displayed in Table 5.4.

Node	0	1	2	3	4	5	6	7	8	9
State	escp	head	head	hop	slave	slave	head	head	head	head
Join	{1}	{0,2}	{1}	{2}	{3}	{6}	{7}	{6,8}	{7,9}	{8}
Rand	3	10	5	2	-	-	6	11	7	12

Table 5.4: Node information in round 3

The important issue in this round is the fact that node 3 which is in the pseudostate of *hoping*, will receive a join message from node 3. This action will lead node 3 to become in *head* again, picking up a new random number to have the change to escape in future time. Table 5.5 will show another round of the algorithm.

When the algorithm ends we can get a result similar to Table 5.6 and the Figure 5.2, but we have to keep in mind that each time that we run the algorithm we can get different results because all depends on the random number that is generated which

Node	0	1	2	3	4	5	6	7	8	9
State	hop	head	head	head	slave	slave	head	head	head	head
Join	{1}	{2}	{1}	{2}	{3}	{6}	{7}	{6,8}	{7,9}	{8}
Rand	3	10	5	7	-	-	6	11	7	12

Table 5.5: Node information in round 4

allow nodes to escape following a certain order.

Node	0	1	2	3	4	5	6	7	8	9
State	slave	head	slave	head	slave	slave	head	head	slave	head
Join	{1}	{-}	{1,3}	{-}	{3}	{6}	{7}	{6}	{7,9}	{-}
Rand	-	10	-	7	-	-	-	11	-	12

Table 5.6: Final result of the algorithm

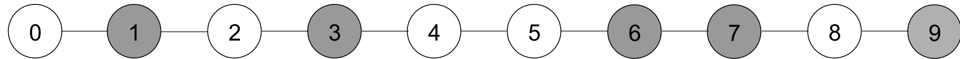


Figure 5.2: CH elected in our algorithm for the chain network

One of the advantages of this algorithm if we compare with the Spohn-Garcia is that we get less heads in this special topologies. For other topologies we can obtain more heads than Spohn algorithm, but our algorithm will always achieve a good performance. On the other hand the drawback of the protocol is that it takes some undefined rounds (as Spohn but not fixed round like LEACH) to converge as well as it has to send a lot if messages.

6 Design problems

During the implementation of the algorithms problems sometimes arises that are not directly related with itself but it is mandatory to figure out them to run the algorithm properly. For example most of them assumes that each nodes knows its neighbour. In our case if we want to run the algorithm in the network or in the simulator, we have to solve these assumptions and find out which are our neighbours. Some of troubles cited below could be the topic of a whole thesis, however in this work we won't go into deep and we will choose just a suitable solution.

In this chapter we discuss which are these problems found during the implementation of the algorithms and how to work out them .

6.1 How to know who are my neighbours?

The easy approach assumes that all nodes are placed on a fixed point in a grid. To know which are my next-hop neighbours, we just have to look the nodes that are located above, on the right, on the left and down of me. It is very easy to find out this because all nodes have a fixed position in the grid ((x,y) coordinates) and it is easy to guess what is next to me. For example we can write an algorithm that define that nodes which are separated only one column or row are 1-hop from mine. If they are one row and column far from me are 2-hop (Figure 6.1). A pseudocode of that is listed below:

The drawbacks of this scheme is that all nodes have to be placed in the grid. For the simulation maybe is not a huge problem, because we could hide nodes and we can make topologies like this:

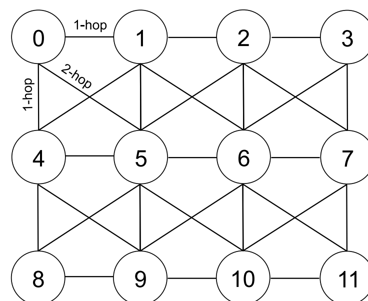


Figure 6.1: Grid topology with 12 nodes

Algorithm 6.1 Distance between nodes

```
1  int distanceBetweenXY(int ax,int ay,int bx,int by)
2  {
3      return (bx - ax) * (bx-ax) + (by - ay) * (by-ay);
4  }
5
6  int distanceBetween(int aid,uint bid) {
7      int ax = aid % COLUMNS;
8      int ay = aid / COLUMNS;
9      int bx = bid % COLUMNS;
10     int by = bid / COLUMNS;
11     return distanceBetweenXY(ax, ay, bx, by);
12 }
13
14 int distance(int id, int id2) {
15     return distanceBetween(id, id2);
16 }
```

Nevertheless it's not a real situation. If instead of testing the network in TOSSIM we run the nodes in a real enviorment, nodes are deployed randomly and it's almost sure that they won't be distributed as a grid topology. Thus, this schema is only useful for the simulator.

For the reason, we have to design a better approach which will serve to run the network for both cases: the simulator and the real enviorment.

6.1.1 The realistic solution

The second solution is based on sending and receiving messages from my one hop neighbours. First of all we will send a broadcast announcement message to advertise all my one hop neighbours that I'm alive. After this, I know which are my neighbours and they know me due to the announcement message exchange. Now if I want to know which are my n-hop neighbours I have to send a packet to my one hop neighbours with two information fields: a *counter* = *n* and a *sender* set to my ID node. When they received the message, they decrease the counter in one unit and they will check if the counter is greater than 0. If it is, they will forward the message to its one hop neighbours. In other case they will save the field sender as my n-hop neighbour. Figure 6.3 represents the above.

The latter entails that depending on the how many n-hop neighbours we want to find out, it may have a packet flooding. Because of a lot of packets are being sending

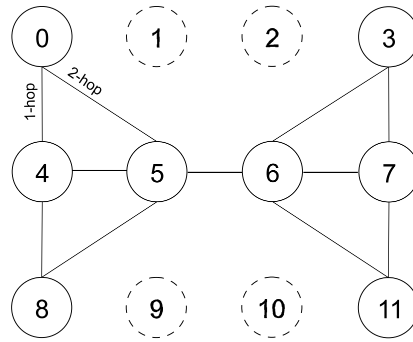


Figure 6.2: Grid topologies with holes

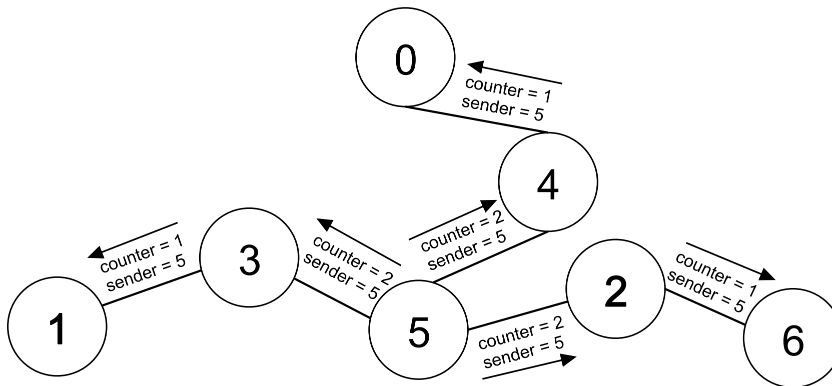


Figure 6.3: Node 5 neighbour 2-hop announcement in a tree topology

and receiving, they may have collisions and some may be lost. Collisions and packet loss are others problems that we try to find a solution and a good design in section 6.2. In fact, this approach let us to design more complex topologies such as tree or random deployed nodes not just grid topologies.

6.2 Packet collisions

When two or more nodes attempt to transmit a packet at the same time, there is a collision. If this occurs we have to discard the packet and retransmitted, otherwise the integrity of the message is not guarantee. For this reason collisions have always to be taken into account when we design routing algorithms. However there a lot of protocols that tries to avoid this situation like: CSMA/CD, CSMA/CA, etc. In wireless network the most common protocol for access to the medium and prevent collisions is CMSA/CA.

TOSSIM simulator has implemented the CSMA protocol. Even though the probabil-

ity for two nodes to start to transmit at the same time is very small, there is always that possibility. If this happen, the receiver will hear the overlap of the signals which it's almost certainly a corrupted packet. Because of that collisions can happen we need an extra mechanism to ensure that the packet arrives to the target properly. That is an acknowledgment extra message.

An acknowledgment is a packet sent to confirm that a message has come and moreover it has come correctly. With this feature if we don't receive the ACK message in a certain time, we will retransmit the packet. TOSSIM has a component that implement the ACK message. If we want to use it we have just to indicate when we send a message that we want the return ACK message from the receiver. On the other hand, if we wait a while and we don't receive the ACK we will retransmit the packet.

6.2.1 The broadcast ACK problem

The latter serves for all unicast packet, but what happens with the broadcast messages? If we broadcast a packet, we don't know how many nodes the signal reach. Thus, we can't guess how many ACK we have to receive and also it's impossible to know if we have to relay the packet to a particular node. Hence, how can we ensure the integrity of a broadcast message?

There is actually no mechanism to solve this. We will try to send the least possible broadcast message. Instead of this, each node will have neighbours matrix like Table 6.1 representing all the information to reach a determinate node. For the tree topology in figure 6.3, Table 6.1 shows all the information about my neighbours (in this case only 2-hop neighbours). Red row indicates which are my neighbours (1 and 2-hop) and the others rows point out which are my routers to reach the node index on the row. For instance to reach *node 1* I have to rout the packet toward to *node 3*. Thereby if I want to send a message to *mote 6*, we will find the router mote in row 6 set to 1 (that is node 2). So we will send a packet to *node 2* telling that our target node is *node 6*. Then *sensor 2* will look at its neighbour matrix which is the router to get *node 6* (it is *node 6*). Figure 6.4 also help us to understand this concept. Blue lines represent the first hop (first iteration) and dash lines are the second hop.

This table is built during the neighbours discovery process told before in section 6.1.1. Furthermore there are two points of view to allocate the data in the system. These are either build it as a matrix bool type with maximum size sets as maximum nodes in the network (an approximation) or build as a matrix integer type with size limit fixes to maximum number of neighboours per node. The matrix in Table 6.1 uses a bool type, however the advantages and disadvantages of those approach will be discussed at section 6.3.

Therefore, If we want to simulate a broadcast message and want to send a message to all my 2-hop nodes, first of all we will send a message one per one to all my one-hop

NODE 5	0	1	2	3	4	5	6	...	max_nodes
0					**1**				
1				**1**					
2			**1**						
3				**1**					
4					**1**				
5	**1**	**1**	**1**	**1**	**1**	**1**	**1**		
6			**1**						
...									
max_nodes									

Table 6.1: 2-hop Neighbours Matrix of Figure 6.3 tree topology for node 5

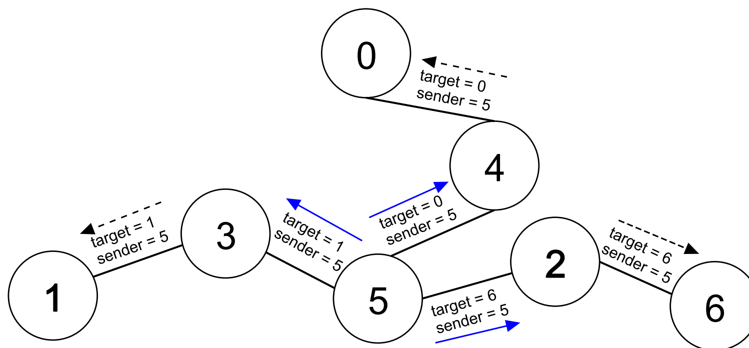


Figure 6.4: Node 5 sending messages to its neighbours

neighbours and they will behave as a router, relaying the packet to my 2-hop neighbour. In this case, sending unicast message instead of multicast messages it's possible to add an ACK mechanism to know if packet arrived properly. If we don't receive the corresponding ACK message from the node which I have sent the packet I will retransmit it.

6.3 Messages and Matrix type

When we started to program one of the first things that I have to deal with was the data types. Because of our applications will run in a mote with restricted memory space and also not very powerful CPU, we have to find the optimum equilibrium between memory allocation and CPU load. It must be remembered that nodes are constrained-battery,so when more time the CPU is working more battery will spend.

TinyOS has small size type of data such as 8 bits unsigned integer or 16 bits unsigned integer that help us to save memory space. In our applications we are going to work

	Node0	Node1	Node2	Node3	Node4	Node5	Node6	Node7	...	Max
Node0	0	**1**	0	**1**	**1**	0	0	0	...	0
Node1	**1**	0	**1**	0	**1**	**1**	**1**	0	...	0
Node2	0	**1**	0	**1**	0	**1**	**1**	**1**	...	0
Node3	0	0	**1**	0	0	0	**1**	**1**	...	0
Node4	**1**	**1**	0	0	0	**1**	0	0	...	0
Node5	**1**	**1**	1	0	**1**	0	**1**	0	...	0
Node6	0	**1**	**1**	**1**	0	**1**	**1**	**1**	...	0
Node7	0	0	**1**	**1**	0	0	**1**	0	...	0
Node 8	0	0	0	0	0	0	0	0	...	0
....	...	...	...	...	...	...	...	...	...	0
Max	0	0	0	0	0	0	0	0	...	0

Table 6.2: Boolean Neighbor Matrix of grid network with 8 motes

with matrix to allocate some important information, so we have to take care to avoid wasting space. At this point we can find two different approaches: uses a boolean matrix or integer matrix. The paragraphs below focuses on what are the advantages and the drawbacks between uses an integer or a boolean matrix.

6.3.1 Boolean Matrix

Suppose that are network is build as a grid topology with 8 motes (Figure 3.1 represents exactly the example). If we want to save in a matrix how are my neighbours we can create a boolean matrix with the size equal to maximum number of nodes in the network. Obviously in a real situation we don't know the exact number of motes, but we can make an approximation. Figure shows the neighbor matrix for all 8 nodes in the grid network and variable *Max* defines the maximum number of nodes.

What are the advantages of this approach? The first big advantage is to know if node 0 is connected with node 3 is very easy, just go to row 0 and column 3. The information is always represented in the same way, thus searching in the neighbour matrix has a constant ($\theta(1)$) cost. Thereby the overload of the CPU is very small. In addition if we compare the size needed in the memory to allocate this matrix is not very high due to boolean type is only one bit. Thus the latter matrix uses 64 bits (excluding how the memory is managed like alignments and so on).

However boolean matrix has also some drawbacks. The first is the size of the matrix. For instance if we are going to deploy a network with 500 nodes is not suitable to have a matrix of 500x500 (*Max* parameter would be five hundred). Furthermore to set matrix's limit we need to know the number of nodes in the network and that is not viable. Besides, we are wasting memory space because of nodes usually don't have more than

10 neighbours, and it means that to store which are my ten neighbours we are using 500 bits. In addition, and this is a negative point to take into account, when we are sending data (like the neighbour list) the data field for the message in TinyOS doesn't allow to send more than 15 bytes. So for the example of 500 nodes we coudn't send the neighbor list message because the data is too big. One solution to avoid that overflow is to send only the nodes that really are my neighbours (set to one in neighbour matrix), but if we do this we are increasing to cost to send a message to $\theta(n)$. Thus, knowing that sending message is a commonly operation, if at the end we are going to send just those nodes which are my neighbours, maybe it's better to save only those neighbours in the matrix. The second approach is based on that and we will go into deep in the next subsection.

Moreover imagine that we want to send a message to all our neighbours. We know that TinyOS is a event driven system, so we can have a timer component that fires every x milliseconds. Thereby, every time that the clock fires we can send a message to one neighbours. For instance we want to node 0 send a message to all its neighbour. At the first timer fired, we check in the neighbour matrix (Table 6.2) if node 1 is my neighbour and if is, I will send a message. Suddenly in the next fired we will check if the node is connected with node 2 and if it is true, it will transmit a message. Later in the third fired we will look at node 3 and so on. We will repeat this process until the last vector's element (in the example above the last node was five hundred). With this scenario we will waste a lot of time (if the timer fired every 10 milliseconds, in the example we will use 50 seconds just for sending one message to all my neighbours that maybe are only ten).

At least but not at last, the nature of boolean type doesn't make it suitable for store all kind of data. Boolean is just a 0 or 1, and we need sometimes to store more complex information like which is the sender of the packet or what is the distance between two sensors. In this case only 1 bit is not sufficient and we must to resort to other data types.

6.3.2 Integer Matrix

Instead of having a matrix with all the nodes in the network, we are going to have only those which are my neighbours. The following table represents that solution for a network with 8 sensors.

The advantages of these solutions are several. First of all we are going to save in our matrix the nodes which are my neighbours. This allow us to reduce the memory space. Instead of having each node a field for all the nodes (500 bits per node in the previous example), we are going to limit the size of the matrix to an approximation of how many neighbours per nodes we will have. As we said before, this maximum number of neighbours usually never exceeds ten. Consequently we are decreasing the matrix length, but we have to notice that now the vector type is integer. Bear in mind that TinyOS has special types such as 8 bits unsigned integer, so we will declare the

	0	1	2	3	4	5	6	7	...	max_neighbours
Node0	**1**	**4**	**5**							
Node1	**0**	**2**	**4**	**5**	**6**					
Node2	**1**	**3**	**5**	**6**	**7**					
Node3	**2**	**6**	**7**							
Node4	**0**	**1**	**5**							
Node5	**0**	**1**	**2**	**4**	**6**					
Node6	**1**	**2**	**3**	**5**	**7**					
Node7	**2**	**3**	**6**							
...										
max_neighbours										

Table 6.3: Integer Neighbor Matrix of grid network with 8 motes

matrix as this type.

Another advantage of this approach is that we can directly send a message of this vector (is not necessary any conversion like in boolean matrix). If node 0 want to announce which are its neighbors, it has just to send its list (that contains nodes 1,4 and 5). This simplifies the sending and the cost of that is $\theta(1)$. However if we want to know if the node 5 is a neighbour of 0, we have to go through all the vector position per position and do the comparison ($\theta(n)$). This is a clear disadvantage due to this kind of comparison is a taks that often happens.

6.3.3 The solution adopted

As in a lot of other things happens, the best solution is not black or white, sometimes the best choice is a mix between both. That is exactly what we will do. For some purpose it's better the boolean matrix, and in other cases integer approach is better. Thus depending on which kind of data we are going to store and which operation are we going to execute more times will choose one type or the other. For example for the neighbor matrix (as we can see in Table 6.1) it's very easy to check if a determinate node is my neighbours. But realistic situation we are going to send packets only to our one-hop neighbours as the in Figure 6.4. Consequently it's better to have an integer vector with my one-hop neighbours (we will discuss this further on in section 6.4) because this vector is shorter and more compact and will allow us don't waste too many clock ticks.

However as we mentioned before, in some cases boolean type can't store all the data that we receive (we need a more appropriate type of data like integer) and it is better the integer matrix. In addition sometimes it's better to have integer vectors (they have a more compact information), otherwise we will waste a lot of time doing nothing.

6.4 Synchronization

In all distributed system synchronization is a big problem that all the programmers have to deal with. In this section we will not address the issue of how to sincrhonizate the nodes with the others when they start to run in the network (there are many algorithms that allows a new node to synchronized with the system). In these paragraphs we will be aware of the importance of don't desyncrhonizate during the program execution.

If we are running the network in the simulator, we haven't got any problem to synchronized the nodes at the beginning because TOSSIM help us to this task. The thing would be worse if we deploy the network in a real enviorment, but we are going to focus only if we use the simulator.

The main task of all nodes are sending and receiving. Because we are interested only in sending packets to our fist hop neighbor (then those will relay the message to the target node), the vector that we will access more often will be the one-hop neighbor list. That seems like this:

Node 0	**1**	**4**				...	
Node 1	**0**	**2**	**5**			...	
Node 5	**1**	**4**	**5**	**6**		...	
Node 11	**7**	**10**				...	
	0	1	2	3	4	...	max_neighbours

Table 6.4: One-hop neighbour list of several nodes in a grid topology (Figure 6.1)

Let's take an example to show what happens if the sensors are not syncrhonizated. In any algorithm when a new round starts, it's common at the beginning to send some messages to our neighbours. Thus, in each time that clock fired, we will transmit a packet to one node. In the first fired we send to the node located at position 0. In next alarm fired we will transmit to the node at position 1 in the vector and so on. Thereby we can realize that there are nodes (like 1 or 11) that have to wait doing nothing until timer counter arrives to *max_neighbours.* Regardless we are wasting time we are forced to wait, otherwise some nodes could preempt others and data structures might not be consistent.

We must not lost the sight of the fact that *max_neighbour* is a critical parameter. If we define that parameter too large, the most part of the time nodes will be idle. For instance just for sending an announcement to all my neighbours if we set *max_neighbours* equal to *30* and the timer fires every 100 milliseconds we will spend 3 seconds to send only one packet to all my one-hop neighours. On the contrary if the parameter is too low (for example fixed to 3), and we have more neighbours than this value, we can't allocate the data of all motes.

To sum it up all nodes have to keep syncrhonizated, despite of that means that they are wasting time. This can be minimized adjusting the critical parameter *max_neighbours.*

6.5 Fragmentation

Our TinyOS header field each packet has the following fields: type of message, source of message, packet sequence number, number of fragment and data. For each of these fields we can use 1 Byte and it will be enough (255 is the largest value because the data type is unsigned integer), except for source field, which the TinyOS standard says that the default type of data is an unsigned integer of 16 bits (2Bytes or what is the same 65535 possibles nodes in the network). If we sum up all the required values we have a header of 5 Bytes.

In TinyOS the maximum data payload is 28 Bytes, so for the data we only have 23 Bytes left. If this were not enough, we need a two dimensional vector in the data field where the first dimension denotes the node ID and the second the information attached to the node. Besides the type of data of this vector has to be again an unsigned integer of 16 bits. Thus if we had 23 Bytes for data, now we have to divided it by two due to the two dimensional vector and at the end we have only 11 Bytes. This entails that we can only allocate 5 memory locations of 2 Bytes. The Figure 6.5 will represent all the header fields and its corresponding size.

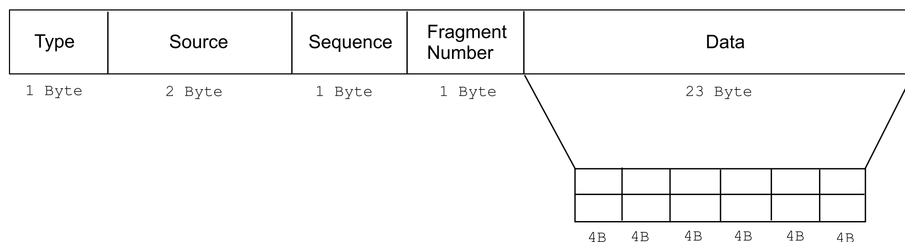


Figure 6.5: Header fields and sizes

The standard MAC that TinyOS includes doesn't support fragmentation. It has been development another MAC for TinyOS that support fragmentation and more advanced features such as s-mac or t-mac. In our case, we are going to keep the predefined MAC and we will calculate by hand how many packet we will need and we will send them. As we have seen above, if the data is quite large we will need several fragments but if the number of fragments it too high our algorithm will take a long time to finish because it has to transmit a lot messages. To figure out these problem we can compress the data before sending the packet. These solution will be explained in the Section 6.6.

6.6 Data compression

Because of the quantity of data that we can send in one packet is quite small, we have to look for alternatives to achieve sending more data information in fewer packets. One of approach is to compress data before transmitting. The latter means that we have to join various kind of messages information in only one. To accomplish this we have to assign some bits of the message field for one type of data and the rest of the bits for the other type of information.

In our case, each position of the message data field is an unsigned integer of 16 bits, so 65535 is the largest number that a memory position can allocate. If we are going to represent in one dimension of the vector the node id, the biggest node id is 65535 and that entails that the network can have a maximum of 65535 sensors. That number seems too much for a normal network. Thus, we can take two bits of this number (for instance the two highest bits) to encode another information. The same principle can be adopted for the second dimension of the vector. We can use the two highest bits for our purpose. If we do this, the maximum number that we can store will be 2^{14}-1=16383 (that is enough number of nodes for a normal network). But now we have four bits left to save another kind of information such as TTL, state, etc. This compression will help us to reduce the number of packets sent. Figure 6.6 shows the desire allocation of the bits.

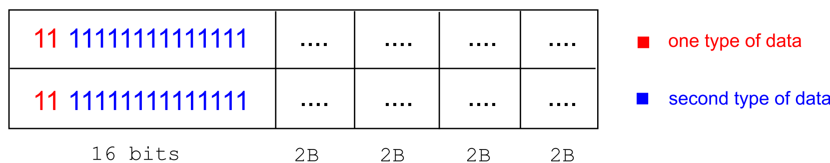


Figure 6.6: Data message field bits distribution

6.7 Tree implementation

For the last algorithm (Chapter 5) we need a tree data structure to save all the possible paths between our neighborhood. There are many ways to implement this data structure but essentially we can split all of them into: dynamic approach and static approach.

If we are going to use the first approximation we can allocate memory dynamically while the tree nodes are coming from our neighbors. Thus, we don't need to specify at the beginning how much memory do we need and we will only use the exact amount of memory that we require. Besides, we have to keep in mind that later we are going to do some operations in the tree as cut branches or merge same nodes, so it's important that

the complexity of these operations don't be so high. With a pointer tree implementation some of these function could be done easily with a good cost. In spite of all those advantages, TinyOS discourages dynamic memory. The reason is that TinyOS stack doesn't have space for heap and even thought that is possible to compile a code with dynamic memory, it is very dangerous because in any moment could be an overflow.

The second approach is to use static memory. TinyOS handles it very good, but it's less intuitive for a tree implementation and also you have to define first how much memory are you going to allocate. This could be a parameter in the header file, but you have to fix it properly otherwise the algorithm will not work accurately.

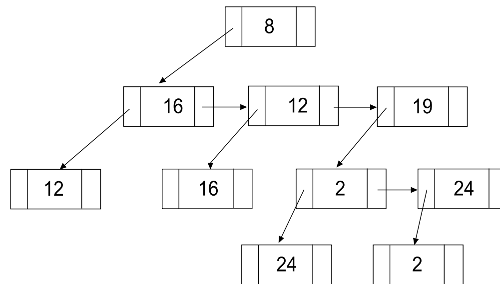


Figure 6.7: Dynamic representation: left son pointer, right brother pointer and node id.

In our algorithm because we can't use dynamic memory in TinyOS, we are going to use static memory but using the pointers representation. In dynamic memory a good representation of a node could be a left son right brother representation That is: a left pointer to the our son, a right pointer to our brother, and the node Id (see Figure 6.7). Thus, if we want to do the same but in static memory we need a three dimensions array where:

- First dimension: allocate the node Id.
- Second dimension: save the index of our son.
- Third dimension: save the index of our brother.

With these model we can port the pointers idea to a static memory allocation. The next illustrations will help us to understand better our idea. If we have the network of the Figure 6.8 and we want to know the three hop neighborhood (without repeat nodes) we will get the right part of the Figure 6.8. If we represent the tree with the pointer structure we will get the memory representation of the Figure 6.7 meanwhile if you chose the static design we will have the Figure 6.9. If we compare both solutions are equals.

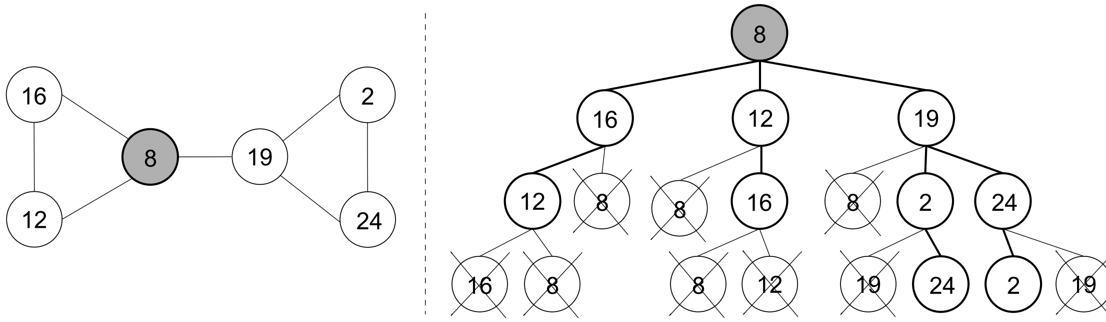


Figure 6.8: Example of network (left part) and the 3-hop of node 8 neighborhood represented by a tree (right part)

	0	1	2	3	4	5	6	7	8	9	...	max_tree
node Id	8	16	12	19	12	16	2	24	24	2	...	
left son	1	4	5	6	-	-	8	9	-	-	...	
right brother	-	2	3	3	-	-	7	7	-	-	....	

Figure 6.9: Static representation of the Figure 6.8

	node 16	node 12	node 19	node 8 neighborhood tree
hop 1	16	12	19	8{16,12,19}
hop 2	12,8	8,16	8,2,24	8{16{12},12{16},19{24,2}}
hop 3	8,19,12	8,19,2,24	16,12,24,2	8{16{12},12{16},19{24{2},2{24}}}

Table 6.5: Tree transmissions for node 8

Another important issues is how to transmit the tree information to our neighbors. He have to remember that in each packet we only have space for the data of 5 nodes (check Figure 6.5). Hence instead of sending every time the whole tree that we have received to our neighbor, we just send the new nodes that collect. Table 6.5 illustrates a complete round for the node 5 and at the end as we can see the tree that we finally get is the same as in Figure 6.8, Figure 6.7 (dynamic representation) and Figure 6.9 (static representation).

7 Security Analisys

Security is an important issue for WSN by the fact that they can be set up in critical systems like airports or hospitals, burglar alarms, military applications, enviorment control or monitoring any kind of activity. Even thought their constraints limit our capacities to add the classic security mechanisms to the sensors hardware and software, we have to come up with new techniques to avoid an intruder to steal or manipulate the data that could cause a disaster.

The goals of the any secure system is to provide confidentiality, integrity and availability (CIA) for the data, protecting information from unauthorized access, use, disclosure, disruption, modification or destruction [1]. Cryptographic functions are usually used to assure these, but because of lack of memory and power in the sensors, most of these approaches can not be converted directly from the traditional security systems to WSN. Besides as happened in the early days of Internet, WSN clustering protocols are not designed for security and they are insecure.

Thus we have to think new mechanisms to add a security layer to our sensors. Some researches have been studying this issues and they have already implemented cryptographic methods. For example, TinyOS 1.0 has a module called TinySec that provide a link layer security architecture. If we are using the new TinyOS 2.0 or 2.1, few month ago a new implementation for AES have been developed for MICAz over TinyOS. But the problem is that for TOSSIM there is not any HAL on the simulator to emulate the behavior of the cryptographic module.

In the next sections we will study which are the most common attacks for a WSN and how can these threats be used against the algorithms described in before chapters.

7.1 Attacks in WSN

Security attacks can be split into two big categories: passive and active. In a passive attack the intruder does not transmit anything to try to confuse the network, it just stand and listen what the other are sending. This kind of attack try to break the confidentiality premise, because it is listening a conversation that is not addressed to him. On the other hand, with the active attacks malicious transmit something in other to corrupt the normal operation of the network and nodes. This kind of attacks are more dangerous and can endanger the confidentiality, the integrity and the availability of the nodes.

WSN uses radio frequency (RF) to transmit over the wireless medium. This fact, make the think easier for an intruder to tamp passive attacks, because any node which a properly antenna can receive the information sent by the others. If the sensor behaves as a legitimate node, any packet sent by others where its target is not the node itself, the sensor will discard this packet (unless it was a broadcast message). But if there is an illegitimate node inside the network, it only has to hide and listen the medium to collect all the data transmitted between nodes. Passive attacks are difficult to detect and if the data is there not any authentication or chyper, these can be easily carried out with dangerous impact.

Passive attacks can be divided in two categories: eavesdropping and traffic analysis. Eavesdropping entails listening the medium and see the content of the packets in order to break the privacy or the confidentiality of a node. For example when we are monitoring any kind of activity through the sensors an eavesdropping attack can recollect this private information. On the contrary traffic analysis try to find out if there is any pattern within the network. For example, we can guess the network topology and which nodes are the CH, which is a very useful information for further attacks.

Active attacks can be grouped in: physical, masquerade/replay/message modification, denial of service and misbehaving. The Figure 7.1 can give us a better description [8].

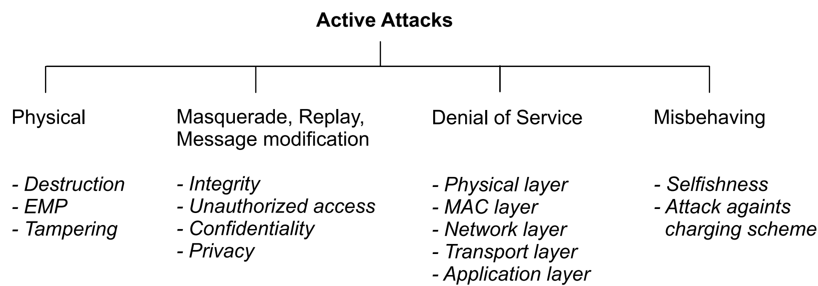


Figure 7.1: Active attacks

Psychical attacks happen when malicious have psychical access to the device. If this occurs the attacker can damage the hardware and kill the sensor. In the case of the network hasn't support fault-tolerant the prize paid for this attack could be even higher.

An adversary can be hidden inside the network, receives the corresponding messages of the cluster algorithm and then modified this message and replay into the network. If the malicious node inject wrong beacons to cluster formation protocol it may modify in one's own way to achieve its goals. This is what is used masquerade, message modification and replay attack.

Denial of service (DoS) includes a broad kind of attacks and their attempt is to make a resource unavailable to its intended users. DoS can be made at any layer, for instance

at psychical layer we can cause DoS in a sensor with just emit another signal with the same frequency near the node. This will cause a lot of noise in the carrier, so the receiver node can not receive the information properly. In the link layer various DoS can be done successful depending on the medium access control (MAC) that the sensors have implemented. MAC for TinyOS is just CSMA, unlike Wifi standard (802.11b/g) uses CSMA/CA and RTS/CTS packets to solve the problem of hidden terminals and exposed terminals. Regarding RTS/CTS is not available in TinyOS the problem of the hidden terminal is always present. Thus a node A that is ready to transmit will transmit to node B because he does not see the malicious terminal C (according to CSMA) and the C sensor can be transmitting always and cause a collisions in node B, so node B will never receive the signal of A. In this case, the node C will have the resource (node B) always for him, meanwhile node A can never get the source. This latter behavior can also be included as misbehaving category. Furthermore the continuous retransmissions of the packet for node A can also deplete the node battery. In the network layer where clustering algorithms work a illegitimate node can refuse message or alter it to not follow the algorithm and avoid node to communicates with others and form properly clusters. Finally at the transport layer the ACK mechanism and messages can be manipulated to jam some nodes.

We should also mention that we can have two different kind of attackers: node-attacker and laptop-attacker. The last one has more powerful hardware, so they have more battery, more CPU resources, more memory and best antenna which can reach further distances than a normal mote. All of these advantages against the nodes, make laptop-attacker very hazardous for our network.

7.2 Security threats in TinyOS

TinyOS is very vulnerably to the attacks at layer 1 and 2. At layer 1 an intruder might jam a carrier just only transmitting a signal at the same frequency near the victim node. This jam cause a DoS in the victim. In this case, TinyOS in not guilty, because the breakdown is due to physics issues more than the way that the operative systems manages the resources. Hence this attack at layer 1 will works in all WSN with any OS. However at layer 2, TinyOS has a implementation of the MAC protocol that is very easy to collapse. As we discuss in the above section the OS uses only CSMA to access to the medium which leads us a possible scene with the hidden terminal problem. A malign sensor C that node A doesn't see can transmit data to node B on purpose originating that node B doesn't receive the message from A properly due to the noise between both signal (A and C). This situation can be avoided using RTS/CTS messages, but because a good reasons TinyOS doesn't adopt them.

Another layer that can be attacked is the transport layer. We can use ACK mechanism

to assure that a unicast packet has been received in the target a node. But it might be a double-edged sword for our cluster algorithm, because if some node try to send a message to another node and this doesn't answer after X tries (this means that doesn't receive the ACK) the node will be remove from the neighbor list (the node looks like be shutdown). Thus, we can make some noise in the node to not let him to reply with the ACK message and after a while this node will be isolate from the network (all neighbors will have delete it from the neighbor list).

7.3 LEACH Algorithm

LEACH algorithm was described in Chapter 2, therefore here we are going to analyze which are the security threats and possible attacks to carry out only in the network layer (the clustering algorithm itself).

7.3.1 HELLO flood attack

In LEACH algorithm once the CHs have been chosen based on a probabilistic formula, they have to send a broadcast message to all its neighbors. Then the non-CH nodes have to associate to only one CH based on some discriminatory parameter as strength signal, distance or battery level. LEACH original algorithm chooses the CH with best signal strength. This fact can lead to a malicious (a laptop-attacker with a power antenna) to emit always a strength signal which is best than any node. Thus every sensor in the network, will try to associate to this node. However not all motes will associate with the intruder, because the radio signal is not as powerful as a laptop and they can't reach the adversary node. These lost packets may involve the network to stay in a inconsient state. In other words, the malicious has caused a DoS.

In our own implementation, we don't use the strength signal to associate to the best node. Instead of these, but we use as a discriminatory factor the distance. Because of our motes are placed on a fix grill (we know which are the distance between the nodes) consequently HELLO attack could not been carried out. On the other hand this fixed topology don't give us flexibility to design our own networks.

7.3.2 Sybil attack

Another choice instead of causing a DoS is to deploy strategical malicious nodes in order to forward all the data in the network to our illegitimate motes. This can easy be countered for the matter that LEACH chooses in each round a CH that has not being chosen previously. In this scenario is when Sybil attack comes up. In Sybil attack a single node presents multiple identities [10]. Thus, the adversary can every round changes its identity to appear as a new node for the rest of the network, consequently it

can be chosen again. We can forward all the data from the network to our sensors and then analyze the traffic which is in plain text or make a wormhole to reply the data in another point.

7.3.3 Other attacks

Our LEACH implementation has been developed thinking always that the algorithm is going to be used in the right way. As a consequence of that if the nodes don't follow the normal flow of the algorithm it may drive the network to a inconsistent state. For example, if we have an adversary that is a CH and receive all the data from its children but doesn't send the data aggregation to the sink, this will be waiting until they receive the package from all the CH (causing a DoS).

Another choice is to send messages like associate when is not it right time in the algorithm flow. In case of the associative messages, each packet that the CH receives will allocate slot in the TDMA shadily for the received node, without checking if the node is already in the schedule. If the malicious node send a burst of associative messages, these can lead to a buffer overflow (of the TDMA schedule vector). Even if the algorithm checks for no redundant nodes in the TDMA timetable, the adversary can always uses the Sybil attack to change its identity.

7.4 Distributed cluster (Clique) Algorithm

The distributed cluster formation protocol tries to build consistent clusters after four steps. In each of these steps every node relies on its neighbors tell the true, so at the end they can achieve a common, unique and consistent clique. However if in any of the four phases (see Section 3.2) a malicious inject wrong data, the cluster formation could be altered.

7.4.1 Silence attack

A node which is communicating with a node but keep silence with another one is making a silence attack. In this type of clustering formation this attack can be very dangerous because introduces inconsistency between nodes. At this point, we are going to introduce a new factor: malicious node could have a directional antenna, so they can send message to a desire direction.

In the step 1 of the algorithm an adversary can send announcement message to one neighbor, but be mute to another. This fact, could cause inconsistencies between both neighbors. In our algorithm because of step 2 we order the local maximum clique received, we can chose another clique despite of a node is not in our neighbor list. Hence this attack in this phase will not affect to the network.

But in the step 2 the attack can cause several troubles. Illegitimate nodes can send modified local maximum clique to two of his neighbors two introduce inconsistency between them. For example if node C (malicious) sends to A (normal node) a better clique that includes A and B (normal node), but keep silence and doesn't send the same message to B, then node A will update its clique to the best clique sent by node C. However node B hasn't received this better clique. Thus imagine that B has update its best clique as the set received by A, but actually mote A best clique is the set received by C (which is different from the clique received by B). As we can see this attack can cause inconsistency between two nodes and brakedown the algorithm in next steps.

In the phase each nodes transmit each updated clique to its neighbors. For every node in the final clique list, the sensor check if that node also include me in the list. In others words, nodes must be mutually in both list. As a result of this, a node can add some troubles by sending a modified clique to one node and withhold the message to another.

7.4.2 HELLO, Sybil and Wormhole attacks

Clique algorithm is also sensitive to HELLO attack. Think about a scenario when a malicious node has ID equal to 0 (we can use Sybil attack to achieve this) and then it sends a very powerful signal (from a laptop) that reach all the nodes. Consequently all nodes will include the attacker mote in its neighbor list. For the next phase, the intruder can also create a fake local maximum clique very large to ensure that it will be chosen as the best clique. Moreover this attack could be combined with placed strategically nodes in order to have at least one malicious node in each cluster and then forward the data with a wormhole or just keep it for analyze.

7.5 Distributed bounded-distance multi-clusterhead algorithm

Spohn-Garcia is a clusted based and this fact entails that the protocol is vulnerable to the same attacks as the distributed cluster (clique) protocol. Nevertheless there is a special attack that we have to remark because it's endanger in this protocol: the selective forwarding attack.

7.5.1 Selective forwarding

As we show in the Section 4.2 the formation algorithm is divided in two phases. During the step 1 all nodes have to discover which are their neighbors and later depends on the neighbor list set their status. An evil node can forward the information received

not to all its neighbor and make the victim node to believe that it is not linked to more neighbors. This action can make the cheated sensor to become as a CH node.

In the phase two if the neighborhood doesn't have data consistency between them, it can be a real mesh. One node A could think that it has sent a message to node B, when could be not true if the malicious mote that is in the halfway doesn't forward it to node B. Moreover if a node that has been converted in CH sent the NA packet (to notify its neighbors that it a dominated node) doesn't arrive to its target the addressed node never will know that the status of the node has changed. The same could applied for the notification messages (that tell a node that it has to convert in CH). The result of these can be that the number of CH can increase because nodes don't have all the information and messages from their neighbors.

7.5.2 Others attacks

As we said before Spohn-Garcia protocol is exposed to identical threads as the clique algorithm. A intruder node can accomplish a Sybil attack and set it's Id to 0 (the lowest Id the better it is, because in case of there are more validated CH than the parameter k in our list within the same distance, we will chose k lowest ID). After this, a node could send a NA message declaring itself as a CH. All nodes will add him at the validates CH list and at the end of the algorithm is it likely to be chosen as CH.

7.6 New Distributed multi-clusterhead algorithm

During the analysis of the previous algorithms we have seen a lot of attacks that can be carried out. In this new protocol all of these attacks can also be performed. Moreover we can look into the code to see which parts are more vulnerable.

One of the points that we can exploit in the protocol is the fact that each neighbor node has to allow a head that is attempting to escape. If a malicious sensor doesn't let any of their nodes to escape the number of CH in the network could increase a lot. Besides if we send join messages to all the neighborhood they will become head every sensor.

7.7 Conclusions

Through this chapter we have seen that any kind of attack is easy to carry out with a very dangerous consequences. To prevent these threads the best and effective solution is to make a message authentication for unicast and broadcast message and add a key management protocol to authenticate all sensors against the base station. To fulfill this requirements researching have been investigating and nowadays there are some

alternatives for processors with 8-bits to accomplish this. Maybe security is not as scalable as in other security systems, but the challenge is to think about and develop new security mechanism adjusted for WSN.

Bibliography

[1] Information security. http://en.wikipedia.org/wiki/Information_security.

[2] Micaz datasheet. http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/MICAZ_Datasheet.pdf.

[3] Tinyos. http://en.wikipedia.org/wiki/TinyOS.

[4] Tinyos community forum. http://www.tinyos.net/.

[5] Tinyos mail list. tinyos-help@millennium.berkeley.edu.

[6] Tinyos tutorials. http://docs.tinyos.net/index.php/TinyOS_Tutorials.

[7] Ameer Ahmed Abbasi and Mohamed Younis. A survey on clustering algotihms for wireless sensor networks. *Elsevier*, 2007.

[8] Erdal Cayirci and Chunming Rong. *Security in Wireless Ad Hoc and Sensor Networks*. 2009.

[9] Y.P. Chen, A.L. Liestman, and J. Lui. Ad hoc and sensor networks. *Nova Science Publisher*, Chapter 4: Clustering agorithms for ad hoc wireless networks, 2004.

[10] J. R. Douceur. The sybil attack. *1st International Workshop on Peer-to-Peer Systems*, 2002.

[11] David Gay, Philip Levis, Robert von Behren, Matt Welsh, Eric Brewer, and David Culler. The nesc languaje: A holistic approach to networked embedded systems.

[12] Weisong Shi John Paul Walters, Zhengqiang Liang and Vipin Chaudhary. Wireless sensor network security: A survey. 2006.

[13] Sophia Kaplantzis. Security models for wireless sensor networks. Master's thesis, 2006.

[14] Holger Karl and Andreas Willig. *Protocols and Architectures for Wireless Sensor Networks*. 2005.

[15] Chris Karlof and David Wagner. Secure routing in wireless sensor networks: attacks and countermeasures. *Elsevier*, 2003.

[16] Turgay Korkmaz. Tinyos and nesc programming. `http://www.cs.utsa.edu/~korkmaz/teaching/cn-resources/tinyos/basictinyos2.ppt`, Spring 2009.

[17] Philip Levis. *TinyOS programming*. October 2006.

[18] David Moss. *Introduction to TinyOS 2.x*.

[19] Marco Aurélio Spohn and J.J. Garcia-Luna-Aceves. Bounded-distance multi-clusterhead formation in wireless ad hoc networks. *Elsevier*, 2006.

[20] Kun Sun, Pai Peng, Peng Ning, and Cliff Wang. Secure distributed cluster formation in wireless sensor networks. *University Daily Kansan*.

[21] Yang Li-zhen Wang Xiao-yun and Chen Ke-fei. Sleach: Secure low-energy adaptative clustering hierarchy protocol for wireless sensor networks. *WUJNS*, 2005.