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Computing Systems

Technical Report

On the implications of Interference models for low-power wireless networks

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Abstract

The rapid progress that has realized the wireless sensor network during the last years has permitted a large deployment not only in specific uses but also in common application linked to several areas. This dynamic evolution faces enormous challenges to overcome many constraints characterizing this type of network and affecting the quality of service provided. The energy efficiency is considered as one of the most critical challenges in wireless sensor networks.

To address to this issue, adapting the transmission features in term of power and frequency is necessary. This approach should participate in ameliorating the performance of the wireless sensor network by increasing the connectivity through the network and reducing the interference effect. Our work conducts to an experiment design and implementation showing the correlation between the power control and the frequency on the one hand and the link quality on the other hand.

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On the implications of Interference models for low-power wireless networks

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Dedication

To the memory of my grandfathers, Belgacem and El Mouldi peace to their souls
To my grand mothers Mabrouka and Hallouma

To my dear parents Mohamed and Moufida for their deep love and support during my studies

To my sister Maha
To my brother Oussama

To my uncle Lotfi and his wife Ines
To my aunt Salwa and her husband Mohamed

To all my dear friends
Mahdi, Hsan, Oussama, Borislav, Hazem, Abdelrahmen, Abdlatif

To my lovely Nadia without whose caring support it would not have been possible

To everyone who helped me to complete this work,

To all, I dedicate this work
✍ Maher

Abstract

The rapid progress that has realized the *wireless sensor network* during the last years has permitted a large deployment not only in specific uses but also in common application linked to several areas. This dynamic evolution faces enormous challenges to overcome many constraints characterizing this type of network and affecting the quality of service provided. The energy efficiency is considered as one of the most critical challenges in *wireless sensor networks*.

To address to this issue, adapting the transmission features in term of power and frequency is necessary. This approach should participate in ameliorating the performance of the *wireless sensor network* by increasing the connectivity through the network and reducing the interference effect.

Our work conducts to an experiment design and implementation showing the correlation between the power control and the frequency on the one hand and the link quality on the other hand.

This work was done under the context of our graduation project in the CISTER research unit in Porto-Portugal.

Key words: Wireless sensor network, Connectivity, Interference, Dynamic Resource Adaptation, Contiki.

Forward

This work was carried out as part of my graduation project at «SUP'COM » High School of Communications of Tunis, in collaboration with the research lab CISTER , to obtain the engineering degree in Telecommunications.

***CISTER** (Research Centre in Real-Time Computing Systems) is a top-ranked Research Unit based at the School of Engineering (ISEP) of the Polytechnic Institute of Porto (IPP), Portugal.*

The IPP-HURRAY research group, created in mid 1997, is the core and genesis of the CISTER Research Unit.

HURRAY stands for HUgging Real-time and Reliable Architectures for computing sYstems. Therefore, the research unit focuses its activity in the analysis, design and implementation of real-time and embedded computing systems.

Acknowledgment

*Upon completion of this work, I would like to thank firstly, Mr. Eduardo **TOVAR** , the head of IPP-HURRAY research group , for having hosted me in CISTER.*

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Summary

List of Figures

List of Acronyms

C

CQ Channel Quality

CQI Channel Quality Indicator.

Q

Q-UDG Quasi Unit Disk Graph

L

LPP Lower Power Probing

LPL Lower Power Listening

M

MIS Maximum Independent Set

R

RSSI Received Signal Strength Indicator

S

SNIR Signal to Interference a Noise

U

UDG Unit Disk Graph

UBG Unit Ball Graph

W

WSN Wireless Sensor Network

General Introduction

During the last decades, the advance made in wireless and microelectronics technologies has stimulated the research in the wireless sensor networks. This type of communication systems consists of micro devices called nodes equipped with: processor unit to process the data and handle the node behaviour, sensor to detect physical aspects, memory unit to store the data collected and radio transceiver to communicate. Thanks to the particular features of this component related to the size and the cost, *wireless sensor networks* are generally composed by a large number of nodes which improves the network performance in term of density and avoiding the possible failure effects.

Therefore, WSN present an interesting approach to deploy in different areas such as environmental, industry, military field. The characteristics of the network deployed are basically related to the type of application that requests specific aspects such as density, mobility and transmission rate.

Meanwhile, the nodes composing the *wireless sensor network* are generally constrained in term of resources. Those constraints, basically related to the limited capacities of computing, storing, transmission rate and lifetime, affect the performance on the *wireless sensor network* comparing to the traditional networks and should be taken into account to ensure an intelligent deployment of the networks and considered as a challenging task to make the WSN more reliable and efficient.

Therefore, energy efficiency is considered as a primary requirement in the design of communication protocols for low-power wireless networks, yet supporting new applications with strict service demands, beyond those originally conceived for *wireless sensor networks*, has serious potential to create value and expand the Internet in an unprecedented way. One of the most important aspects in this area is to optimize MAC sub-layer mechanisms in order to efficiently cope with radio interference and improve real-time properties such as capacity and schedulability of low-power wireless networks.

In this context, our work was about focusing on investigating innovative MAC mechanism based on the *Signal to Noise* plus *Interference Ratio* (SNIR) model. For this, we will design experiments to study real-world channel properties for short range radio links that permits to derive algorithm that maximizes spatial reuse of the spectrum and dynamically controls the transmission power in adaptive low-power wireless networks. For this purpose, we use the Contiki operating system for sensor nets.

The present report is divided into three main parts: in the first part we represent a general view of the *wireless sensors network* in term of architecture, topologies, characteristics and components and we introduce some theoretical and physical models describing the connectivity and the interference as an important aspect of the wireless networking.

The second part will be related to describe our experiment approach by presenting first the programming model: the Contiki operating system and we will detail our experiment design taking into account the characteristics of *wireless sensor network* mainly in energy consumption and memory capacity.

The third section will be dedicated to present the simulation and the test results using specific tools which permit to exploit the data collected from the experiment and to describe in clear way the different factors affecting the link quality.

Finally, the report ends with a general conclusion in which we summarize the work done and we present some perspectives that will be the topic of the future work within this research area.

Chapter1: Wireless Sensor Network

Introduction

The wireless sensor networks have become recently a great source of attraction in the research and the industry community thanks to the advancement made in the wireless domain and the digital electronic technologies.

Wireless sensor networks represent many differences comparing to the traditional wireless network related basically to limited energy and memory capacities and the restricted life time In this section, we present an overview of the WSN in term of architecture , applications and characteristics and in particular the connectivity an d the interference features of this type of network.

1.1. WSN's Architecture

The WSN is generally composed by large number of sensors constituting the sensor field. These sensors are interconnected to capture the data and to rout it to a central sensor called sink; permitting to connect the sensor field to other types of network (Internet, Satellite, etc).

In order to manage the network depending on the analysis done on the information collected by the sensors, it transmits the collected data in the sensors to the task manager.

Thus, the WSN architecture is divided to 3 parts:

- *The sensor field*: composed by the motes .The characteristics of the sensor field are for e.g: motes type, geographical distribution of the nodes, the density of the field in sensors, etc. And it depends essentially on the application of the network.
- *The sink*: presents a specific senor of the network. Its role is to collect the data from the motes composing the sensor field and it is designed to have unlimited resources in energy in order to receive information from the sensors at any time. The number of the Sinks in the network depends basically on the amount of related data, the

density of the nodes and the network application and it improves the balancing of the energy consumption among the network.

- *The Task manager*: receives the collected data by the Sink. It is responsible for managing the data gathered by analysis and process in order to extract the useful information. The link between the task manager and the other parts of network is done through another type of network and it is generally Internet which requires the implementation of gateways between the sink and the task manager to adapt the collected and transferred data.

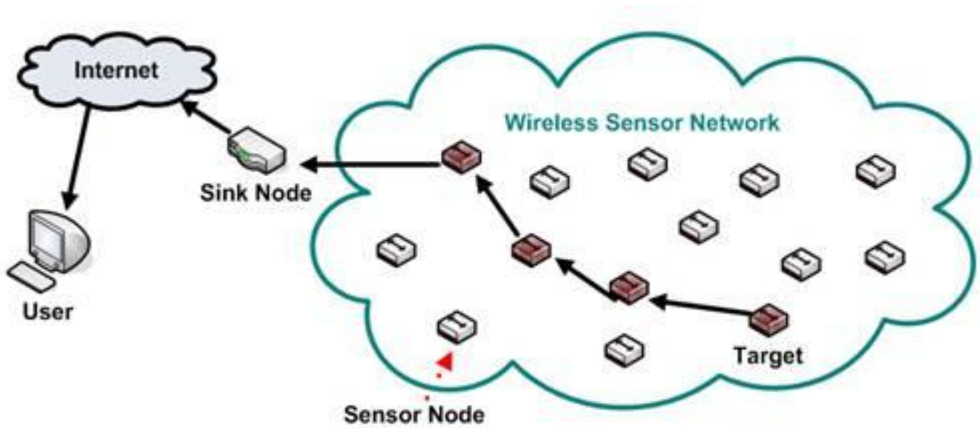

Figure 1. 1 : Wirless Sensor Architecture

1.2. WSN's Topology

The wireless sensor networks have inherited many characteristics of the traditional networks including the topologies. The choice of the topology to be deployed in the WSN depends on the applications delivered by the network and the scale of the network aims to reduce the complexity, the cost and to improve the efficiency. In this section, we present four types of wireless sensor network topologies:

- ✓ *Star topology*: the nodes are connected to a centralized node. All the communication in the network in receiving or transmitting should pass through the centralized sensor called server meanwhile to other nodes are called clients.

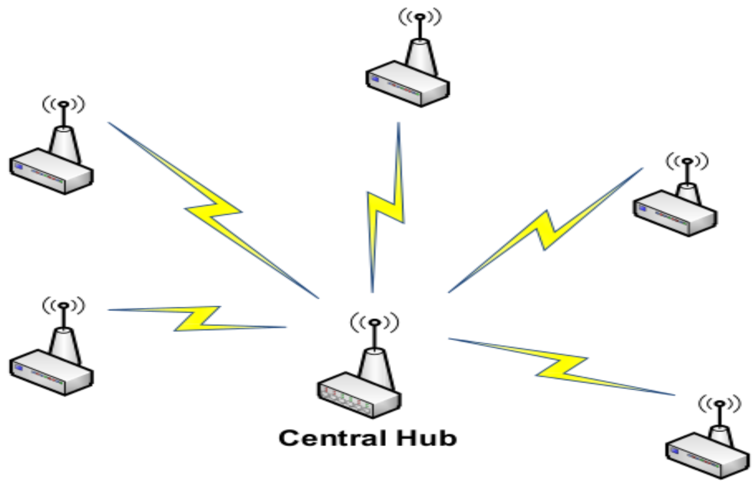

Figure 1. 2 : Star topology

- ✓ *Peer to peer topology*: any node can communicate directly with any other node in the network. The flexibility offered by this topology is considered as the main advantage of this configuration; meanwhile it is so difficult to be controlled.

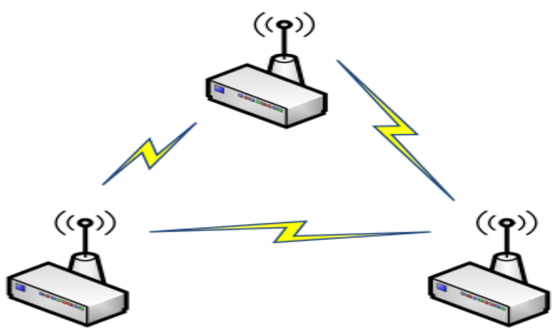

Figure 1. 3 : Peer to peer Topology

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- ✓ *Mesh topology*: the connection between the nodes is based on hopping from node to node to reach the desired destination. This configuration requires self-healing capability in term of routing in case of braking nodes or links. This topology is the most complex and expensive in set-up or in maintenance and contains redundant connection through the network.

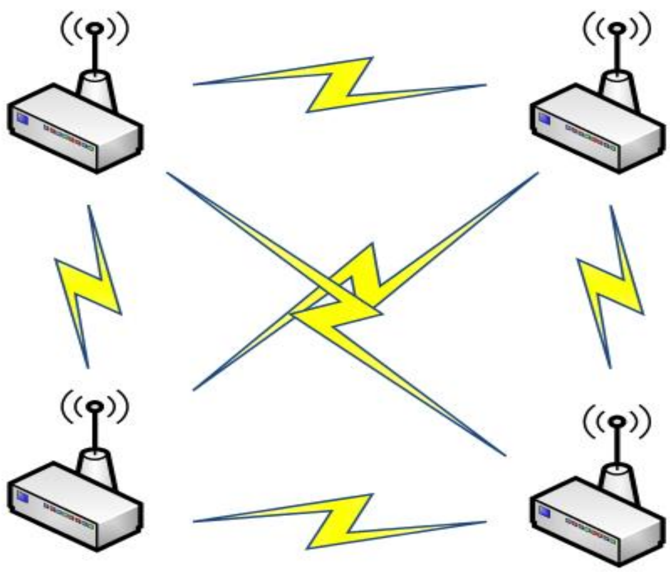

Figure 1. 4 : Mesh Topology

- ✓ *Tree topology*: the configuration is divided into three levels at least. The top of the configuration contains the coordinator (root node). The lower level is composed by star networks connected as children to the coordinator. Therefore, the tree networking is as a combination of the Star and peer to peer topologies.

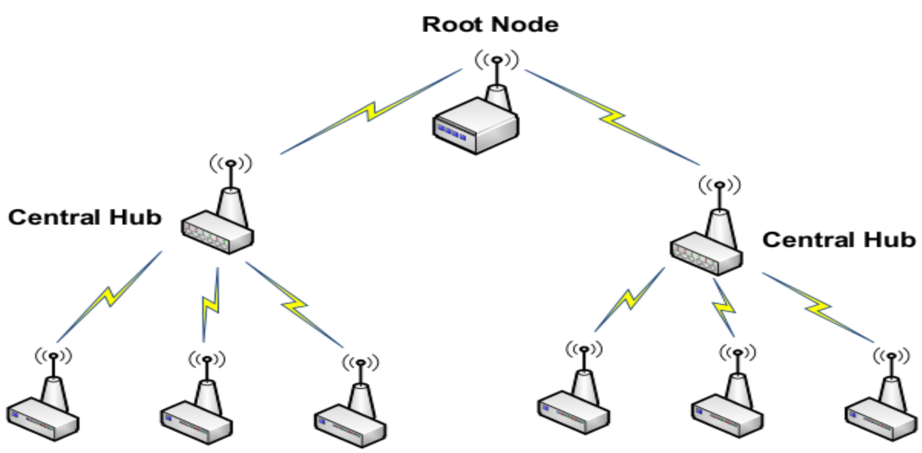

Figure 1. 5 : Tree Topology

1.3. Protocol Architecture

The deployment of the Wireless Sensor Network must take into account:

- ✓ Wireless sensor network protocols and standards e.g Zigbee , IEEE802.15.4, Wireless HART.
- ✓ WSN constraints in term of bandwidth and energy consumption.
- ✓ Network characteristics according to the mobility, the security and the routing.

A proposed solution to standardize the communication through the wireless sensor network is to use a protocol stack. This stack shown in the Figure 1-6 presents a general view of the communication and management protocols in the wireless sensor networks. This configuration consists of:

- Five layers having the same functionalities inherited from the traditional protocol stack : ISO : Application, Transport, Network, Data Link, and Physical.
- Three planes aware of management of: Task, mobility and power.

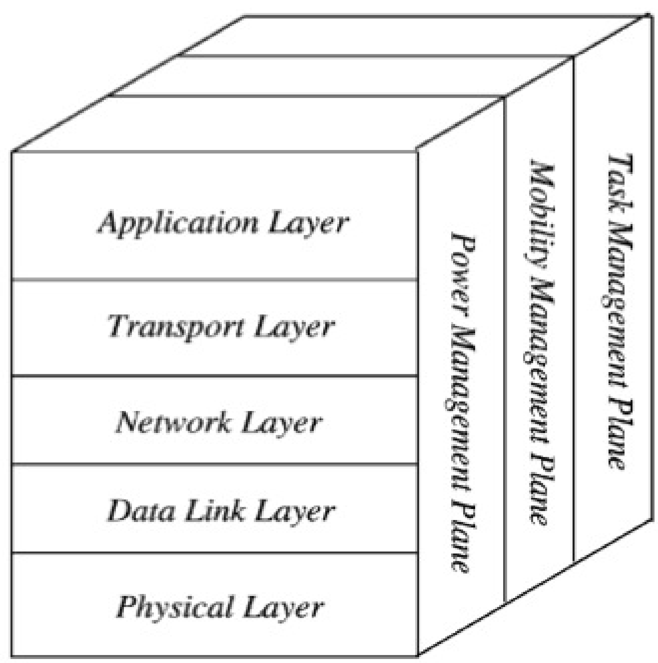

Figure 1. 6 : Protocol Stack

1.3.1. Layers

- ✓ *Physical layer*: responsible of the connectivity in the WSN in term of frequency selection, signal detection and encryption.

- ✓ *Data link layer*: its functions are medium access, data frame detection and error control. The WSN are characterized by typical MAC protocols aiming to establish communication between the nodes that share the resources.
- ✓ *Network layer*: is aware to root the packets taking into account the power efficiency. The routing protocols in the case of the WSN are based on optimization of the energy consumption (determine the best road with the minimal energy consumption and minimal number of hopes).
- ✓ *Transport layer*: its principal role is to interconnected different types of networks. In case of WSN, the communication with the outside world through the sink is not based on global addressing to determine the destination of the packets.
- ✓ Application layer: it enables the interaction with the users. This layer permits as example to aggregate the data or to query the WSN configuration status.

1.3.2. Management planes

We distinguish 3 planes:

- ✓ Task management plane: responsible for the tasks' scheduling and balancing.
- ✓ Mobility management plane: responsible for detecting the nodes movement among the network in order to maintain the data route.
- ✓ Power management plane: permits to control the power consumption considered as one of principal aspects of the WSN.

1.4. Applications

The *wireless sensors network* composed of different types of nodes is able to present a different view in existing applications fields or create new ones. The sensor nodes considering as cheap and simple solution to program and to employ have been using in several areas and have integrated many physical parameters as:

- Temperature
- Humidity
- Vibration
- Visual and infrared light
- Pressure

- Chemical sensors, etc.

Many kinds of applications can be constructed with different types of nodes covering many areas as medical, military, environment and industry.

1.4.1. Environmental Applications

Nowadays *wireless sensor networks* are widely applied in the environmental sensing. Some of the applications covered by the WSN in this area are listed below:

- Forest fire detection: distributed *wireless sensor networks* with large number of nodes are used to detect the source of fire in forest which makes it easier to control and therefore limits its spreading. The large number of nodes and the long term deployment in forests request an efficient system of energy loading.
- Air pollution monitoring: *wireless sensor network* are deployed to detect the gazes concentration in and out the cities with chemical sensors.
- Marine ground floor surveillance: permitting to understand the erosion processes requested to the construction of offshore wind farms.

This was a brief description of the main standards that have defined the IMS concepts.
We will give a more details about its architecture and the related entities and protocols in the next sections.

1.4.2. Military Applications

The military field was one of the first applications of the *wireless sensor networks* taking benefits from the simplicity of infrastructure deployment. This type of network is used to:

- Supervise to battlefield.
- Monitor the equipment the weapons and the vehicles
- Control and detect the non traditional attacks (with nuclear ,biological and chemical weapons)
- Recognize the opposite forces

1.4.3. Industrial Applications

The development of the *wireless sensors network* has aimed to use the industrial field and is deployed now in 216 automation professionals to:

- Data collecting.
- Industrial sense.
- Machine surveillance e.g detecting the vibration pattern or the temperature level to indicate if the machine needs maintenance or not.

1.4.4. Medical Applications

The deployment of the WSN is integrated in the health care applications in order to:

- Connect patient and doctors with sensors in hospitals for tracking.
- Telemonitoring of patient to detect his physiological state.
- Surveillance of elderly and disabled people.

The following figure summarizes the different areas of the wireless sensor networks use:

Figure 1. 7 : WSN Applications Areas

1.5. Wireless Sensor Networks Characteristics and Constraints

The *wireless sensor network*s are composed of a large number of nodes. These nodes are generally deployed for a given application in interest and share several characteristics related essentially to the power consumption, the configuration and network processing.

1.5.1. Dense Deployment

Usually, the sensors nodes are densely deployed and this depends on the service type delivered by the network. Including large number of nodes may vary on time and space to resolve the problem of the mobility or the possible failure of the nodes. The wide range of density in WSN requires that the deployed architecture and protocols must be able to scale the large number of nodes.

1.5.2. Programmability

The role of the nodes in WSN is not restricted to detect and process data, the sensors must be flexible in term of configuration needed to be adapted to changing tasks during the ongoing operation.

1.5.3. Mobility

Many applications demand a dynamic topology of network caused by the movement of the nodes and the changing of locations.

The functioning of the nodes in a given network can be related to the detection of a physical phenomenon requiring a movement processing. Tracking the moving target demands a flexible data organization and gathering to keep it under observation. Moreover, the network topology in case of mobile nodes requires an auto configuration protocol that deals with the nodes localization and organizes the in-network traffic.

1.5.4. Limited Resources

The power supply used in sensor node is usually limited (Batteries) which affects the sensors' performance and make the replacement of the energy source not practical. Hence, the lifetime of the wireless sensor network is considered as an important challenge. Deploying the nodes in an energy-efficient way by organizing the transmission between the nodes and working on ameliorating the MAC layer behaviour present an important purpose of research in this field.

As another option, alternative power sources as solar cells may be used with sensor nodes to provide a continuous power supplying and a source for batteries recharging. Sensor nodes are also limited in computation and storage resources. For instance, the CPU of a mote prototype is 4 MHz with 512 bytes RAM, 512 bytes EEPROM and 8 bytes flash memory.

1.6. Node

Understanding the *wireless sensor networks* functioning depends on discovering the basic part of the network: the sensor nodes; in another word the hardware and software components and mainly how the sensors design meet the essential requirements of the WSN applications. The capabilities of the nodes regarding computing, energy consumption, memory, communication, and sensing compose the principal aspects of the sensor nodes that would be explained in the following part of the first chapter:

✓ Hardware components: the sensor node consists of five basic components:

- Controller
- Communication unit
- Power supply
- Memory
- Sensor

The following figure gives the different node components:

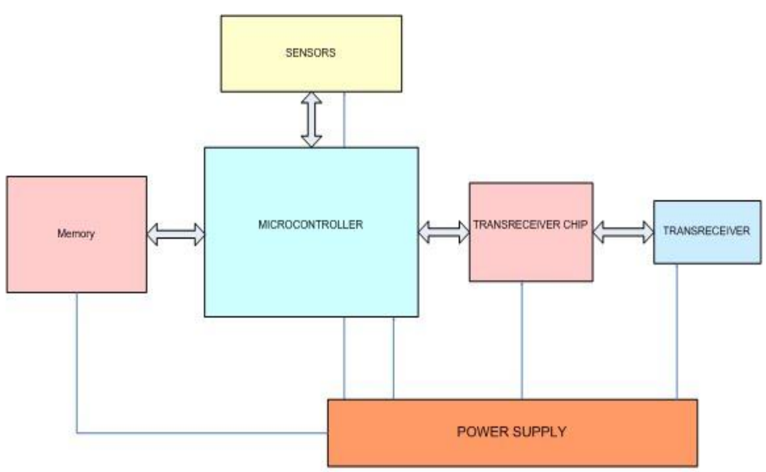

Figure 1. 8 : Node Architecture

- ***Controller***: presents the of the sensor node. It is responsible for collecting the data from the other sensors and coordinating the activities of the node deciding its behavior in term of when and where it should receive and send the data. As a central processor unit of the node, it permits to execute the communication protocols in order to collaborate with the other components of the network. The controller is composed also an *Analog-to-Digital Converter* (ADC) to convert the data measured from analog to digital format to be processed.
- ***Communication unit***: responsible of transmitting and receiving signal over the wireless channel. It permits to convert the bit stream coming from the controller to radio waves and vice versa.
- ***Power supply***: responsible of providing energy to the other parts of the sensor node. Generally, Batteries are used as power source for the sensor nodes. Supplying energy is also done by recharging units.
- ***Memory***: the constraints of the sensor nodes in term of memory present a main issue of research and developing in this area.

The memory unit consists of:

- *Random Access Memory* (RAM): to store immediately the income data from other nodes. It is characterized by the speed of treatment and the loss of content in case of power interruption.
- *Read-Only Memory* (ROM): to store the program code programming the device.
- Flash memory: to store the data or devise program. It is characterized by higher capacity of memory size comparing to the RAM and more consumption concerning time and energy.

- ***Sensor***: presents the physical entity of the sensor and it is used to measure and control the physical parameters of the environment e.g. temperature, light, pressure.

The sensing devices of the node are classified into three categories:

- ✓ passive, omni-directional sensors : measure physical parameters as light , humidity, temperature, etc.
- ✓ passive, narrow-beam sensors : have well defined direction of measurement (similar

functioning as camera).

- ✓ active sensors: are related essentially to the detect the vibration or reflexion produced by waves e.g radar sensor, sonar sensors, etc.

1.7. Connectivity and Interference in WSN

As an important aspect of the wireless networking, the connectivity between the nodes composing the wireless sensor network presents a big field of research to characterize the in-network transmission.

In this section, we present different connectivity models that specify how the nodes interact when they share the communication medium which may cause interference affecting the wireless network capacity.

These models have to take into account the essential parameters affecting the transmission:

- The spatial distribution of the interfering components.
- The transmission characteristics: power, frequency and synchronization.
- The propagation characteristics: path loss, shadowing, multi path, etc.

1.7.1. Unit Disk Graph *(*UDG)

The Unit Disk Graphs UDG **[1]** have been introduced in the 80-90 of the previous century as a part of the geometric graph theory and has been used since 1995 in order to model the interaction in the wireless networks and mainly in ad-hoc wireless communication network.

This graph model considering as a popular modulation of the communication into the wireless networks is basically composed by a collection of vertics in the Euclidean plan representing the wireless sensors which their radio range is modelled as a unit disk.

This model is customized to understand the routing and the media access (MAC) protocols and more specifically the communication between the nodes and the risk of interference in case simultaneous transmissions.

a. Definition

Let P be a set of points in the Euclidean plane. The graph G(V,E) is called unit disk graphs if:

- for each point of P we associate a vertic in V

- Two points are connected if their Euclidean distance is as most 1.

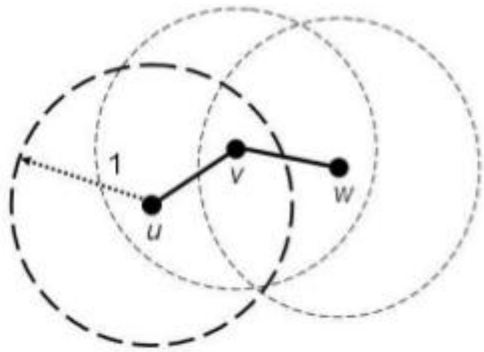

Figure 1. 9 : UDG Concept

In other words, there exits $\Phi : V \rightarrow IR$ satisfying for arbitrary u,v ∈ E if $\|\Phi(u) - \Phi(v)\|_2 \leq 1$

b. Proprieties

The unit disk graph approach assumes a wireless network with :

- identical nodes in term of transmission range and power.
- Euclidean plane in which the node position are modulated.
- Nodes equipped with perfect omni-directional antenna for transmitting and receiving signals.
- A radio range modelled as radius circles.

c. Limits

The UDG considered as the most simplified graph based model and even idealistic since it does not make sense to consider the radio transmission range as circular. Moreover ,it considers the node's antenna as omni-directional. Unless the popularity of this model especially in the WSN simulation tools, it simplifies the connectivity between the nodes and is considered as unrealistic and useless in real-world experiments.

For these reasons, research has been done to propose other models for sensor networks.

1.7.2. Q-UDG

In this model, for each pair of nodes, u and v, with Euclidean distance |u, v| defined as follows:

- ✓ $|u, v| \leq \rho$, for some given $\rho \in [0,1]$, the nodes are adjacent.
- ✓ $|u, v| > 1$, the nodes are never in the same radio coverage area.
- ✓ $\rho < |u, v| < 1$, the nodes may or may not be adjacent.

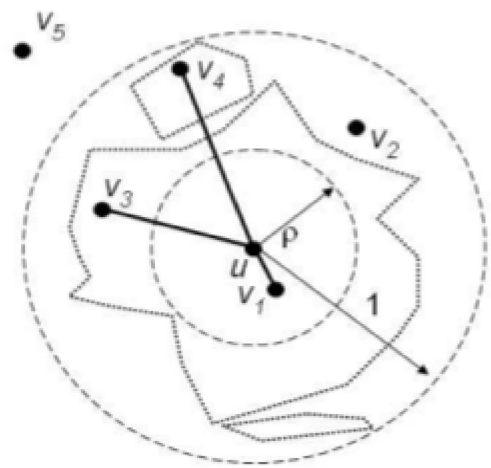

Figure 1. 10 : Q-UDG Concept

The Q-UDG model **[2]** is more flexible and more realistic than the UDG model considering that two nodes are not adjacent due to the imperfection of the radio links. Nevertheless, this model cannot be attractive to model nodes installed in inner-city or in-building where obstacles cannot be neglected, e.g, the communication may be established between two nodes with a distance of dozen of meters but not with two closed nodes in an obstructed environment, i.e ,obstacles may enlarge the probabilistic zone where the nodes may or may not be connected (between ρ and 1) by reducing the value of that tends towards zero in this case.

1.7.3. Unit ball graph

The unit ball graph is another type of modelling of the links between the nodes in a wireless network. This model operate with double metric considering the vertices as point in IR^3 which goes below the unrealistic aspect of UDG model with nodes in a flat world. Let G= (V,E) a graph composed by a set of vetices distribute in double metric space. The ball E is a unit ball graph for a given V if for each u, v ∈ V if and only if the distance between u and v in IR^3 less than or equal to one.

The UBG is a generalization of the UDG model. Moreover, QUDG can be modelled by a UBG with a constant ρ.

1.7.4. Growth-bounded Graph

a. Definition1: (Maximal Independent Set)

For a given graph G = (V, E), a subset S ⊆ V is called independent if it is composed of vertices that cannot communicate directly.

A maximal independent set (MIS) S is an independent set that cannot be extended by addition of any other vertices, i,e an independent set is maximal if no node can be added without violating independence. An example is illustrated in Figure.

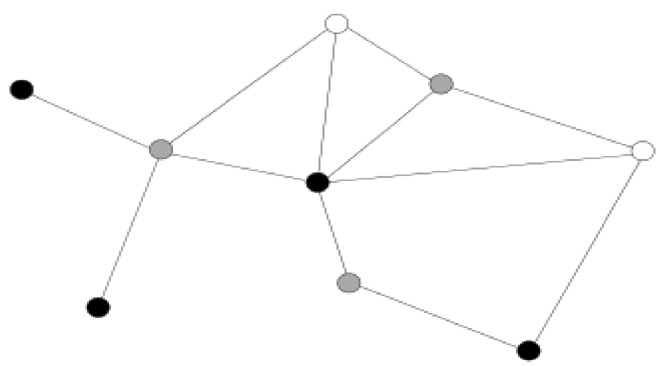

Figure 1. 11 : Maximal Independent set

b. Definition 2

A Graph G=(V,E) is called growth-bounded if there exists a polynomial bounding function f(.) such for every v ∈ V and r ≥ 0, the size of any maximal independent set(MIS) in the r-neighbourhood $N^r(v)$ is as most f(r).

with:

- f(.) : polynomial bounding graph i.e for some constant c ≥ 1 , f(r) = $O(r^c)$ is bounded by a polynomial maximal degree c .
- $N^r(v)$: neighbourhood of the node v i.e all the nodes within r hopes of v.

The function f(.) does not depend on the number of the nodes or any other propriety of G. It only depends on radius of the neighbourhood. Therefore, the number of independent nodes in an r-neighbourhood in constant for each r.

These models oversimplify the physical aspects of the real wireless networks mainly the laws of interference and are able to estimate the interference in indoor scenarios.

1.7.5. SNIR Model

Sharing the communication medium between the nodes of the wireless sensor network make the transmission affected by interference. This physical phenomenon due to the simultaneous transmission of the information among the parts of the network. Blocking the transmission between the nodes caused by Interference affect the capacities of the wireless sensor networks and reduces the information exchanged through the network.

The radio propagation should goes below the fact that only the distance can affect the performance of a given network which is the case of the theoretical models explained previously.

a. Definition

In order to capture the characteristics of the interference, It's necessary to have recourse to realistic model that goes beyond the limitations of theoretical model earlier mentioned . One of these physical model proposed to govern the connection quality is the signal to interference a noise (SNIR) model **[3] .**

In the SINR model 3 parameters are considered:

- the signal of the power received.
- the ambient noise.
- the interference generated by the transmission of the other nodes or by external devices.

A packet is successfully received by a node if a the ratio between the received signal strength and the sum of the ambient noise and the interference exceeds a certain hardware-specific threshold.

Let Pr be the signal power received by a node (r). The signal power Ps fades with distance between the sender (s) and the receiver v following the pathloss model

$$Pr = \frac{Ps}{d(s,r)^{\alpha}}$$

- N be the ambient noise power level also called the background noise represented an form of pollution and interference and modelled as constant noise and
- Iex be the external Interference: It is nor related to the message transmission in the network under control and caused by the coexistence of the system sharing the same frequency band.

The wireless sensor network, operating on unlicensed bands , face the external interference coming from other devices operating in the same frequency bands such as 802.11 WLAN and Bluetooth devices emitting noise on parts of the 2.4 GHz band.

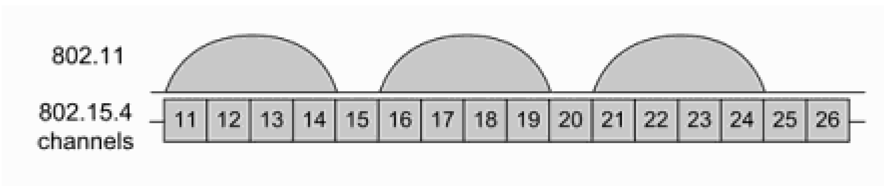

Figure 1. 12 : 802.11 and 802.15.4 channel overlap

- I in be the internal interference. It is due to the collision between packet transmission of the network and may be modelled by the sum of the transmission power level of the nodes with the exception of the sender (s) decaying also with distance :

$$Iin = \sum_{i \in V-(s)} \frac{Pi}{d(i,r)^{\alpha}}$$

- β be the hardware-specific threshold.

Therefore, a packet transmitted from a node(s) is successfully received by a node (r) if:

$$\frac{\frac{Ps}{d(s,r)^{\alpha}}}{N + Iex + \sum_{i \in V-(s)} \frac{Pi}{d(i,r)^{\alpha}}} \geq \beta$$

b. Limits

The SINR is considered as the one of the advanced physical models used to describe the quality of connectivity and qualify the interference effect in the wireless sensor network. Meanwhile, this physical model still has some constraints:

- Some elements of the SNIR inequality are hard to determine such as the path loss exponent that may vary in an obstructed environment which qualify the SNIR model as a simplistic model.
- Representing the reception zones of nodes that constitute the SNIR diagram is difficult to construct mainly with irregular shapes contrary to the theoretical models.

Conclusion

The aspects of the wireless sensor network mainly the limited resources of power and memory represent an important research challenge. A well understanding of these issues related to theoretical and practical characteristics of the WSN is useful to look for the solutions permitting to ameliorate its performance. In this context, we will propose an experimental study of the connectivity through the wireless sensor network.

Chapter 2: Experimental design and implementation

Introduction

In order to define our experimental approach to describe the connectivity through low-power wireless networks we propose in this section to better understand the Contiki programming model in which we implement the code following the experimental design represented in the second part of this chapter.

2.1. Programming Model: Contiki Operating system

2.1.1. Definition

Contiki **[4]** is a dynamic, multitasking and portable operating system designed for networked embedded systems and wireless sensor networks . This popular operating system was released in 2003 by Adam Dunkels member of the Networked Embedded System group at the Swedish Institute of Computer Science (SICS).

Contiki is specially designed for memory constrained microcontrolled systems as the wireless nodes with limited amount of memory with less than of 10 kilobytes of RAM and 50 kilobytes of ROM. It is built around an event-driven kernel and contains, as a multitasking OS, a library of optional functions loaded explicitly by the required program and permits to handle processes. Those processes uses per-emptive multithreading with events the messages passing as well as the protothreads with linear programming style.

Contiki contains two types of communications stacks:

- Rime: a lightweight layered communication stack designed to simplify the implementation of the sensor network protocols.
- uIP : provides Internet Connection abilities to Contiki throw the implementation of the TCP/IP stack

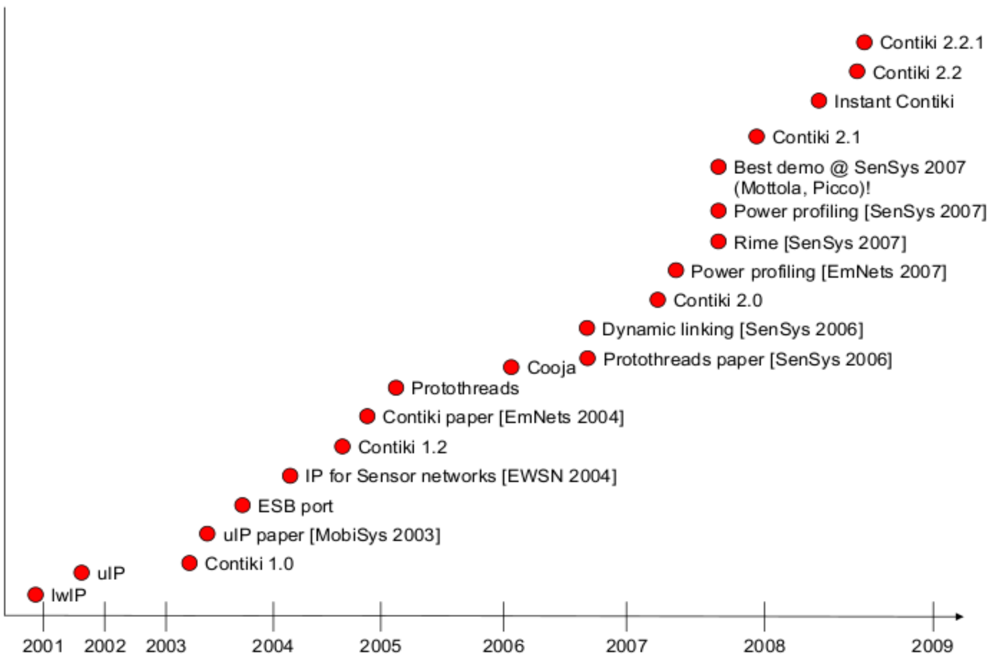

Figure 2. 1 : Contiki Timeline

2.1.2. System architecture

The Contiki core is composed of several elements:

- ✓ Event-based Kernel
- ✓ Program loader
- ✓ Libraries
- ✓ Communication stacks with the hardware driver
- ✓ Management module of the system libraries

This architecture organized in modules allows to load the applications and the subsystem which present the reconfiguration unit of Contiki. Therefore this modular architecture permits to implement and to run efficiently a variety of applications and platforms.

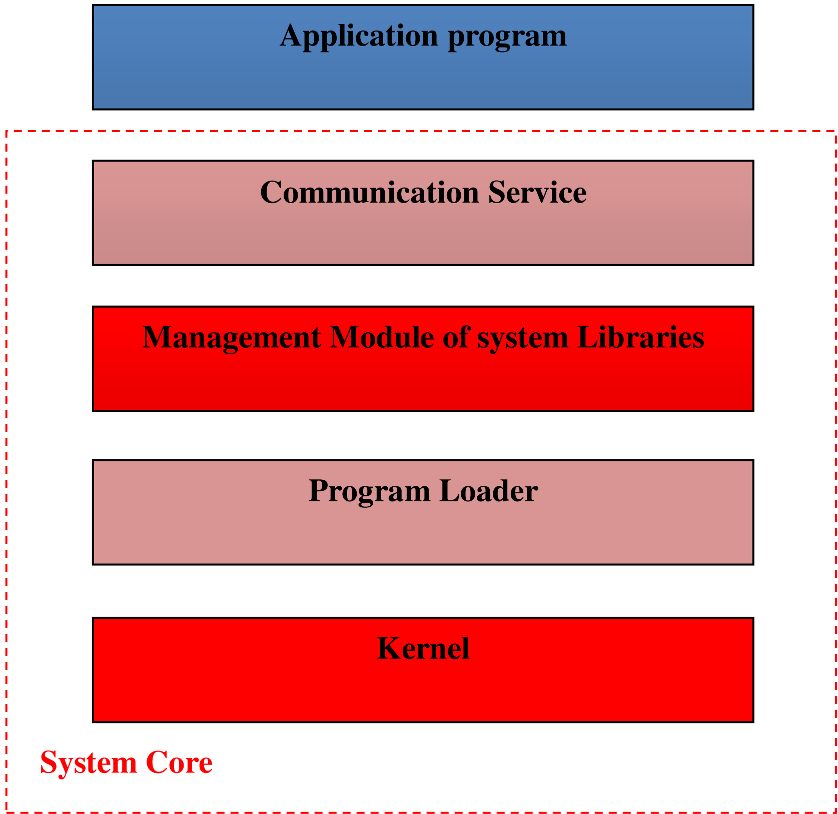

Figure 2. 2 : Contiki System Architecture [Dunckels 2004]

a. The kernel

The Contiki as a real-time operating system provide an event-driven kernel i.e it is applied to handle event by executing the different part of a code on which event is given. The program execution by the kernel depends on the correspond event that triggers it and it is never be interrupted till completion.

The purpose of this design is to handle the processes invocations and to manage the concurrent hardware interrupts related mainly to the events activities and sharing the same the same stack and consequently it requires less memory and computation overhead comparing to others multi-threaded models that involve per-thread stacks.

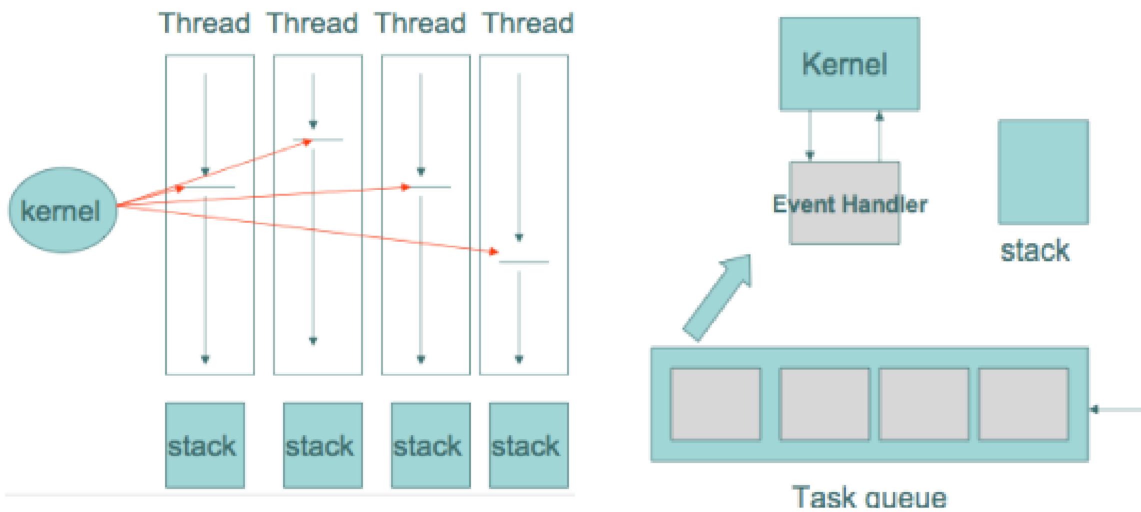

Figure 2. 3 : Multi-threaded and event-driven model

The kernel handle two types of events: synchronous and asynchronous. The first type of events require to be placed in a queue after its triggering and processed after certain delay unlike the synchronous events producing a quasi immediate response.

b. Libraries

The libraries consist of a part of the Contiki operating system. According to its location, it may or may not be reconfigurable. The libraries which constitute a part of the system core considered as static.

Meanwhile, the libraries associated to the application programs are more dynamic and give to the user the opportunity to integrate the modifications that must be controlled in the beginning of the processes to ensure the compatibility. The system core reconfiguration is also possible but more complicated.

c. Protothread

In order to simplify the event-driven programming, Contiki supports a new policy called *Protothreads* developed in 2006 by Adams Dunkels and Oliver Shmidt in a library. The functioning of the protothreads is similar to the event-driven programs in blocking the the processes nevertheless this blocking is conditional and represented by the primitive PT_WAIT_UNTIL(cond). The unblocking is produced if the the condition « cond» is satisfied.

The protothreads are stackless and function with a blocking context using a surplus on the order of single bytes providing therefore a minimal using of memory per protothread (2 bytes of RAM each).

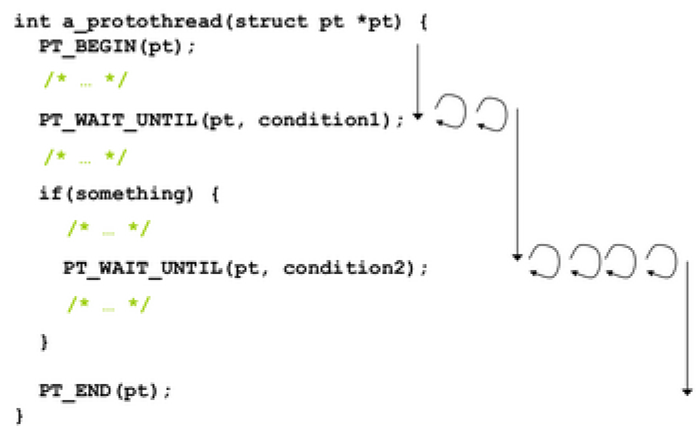

Figure 2. 4 : Protothread example

d. Communication stacks

One of the important challenge of Contiki is to integrate the communication services in such a way we avoid the complexity of the traditional layered communication architectures taking into account the constraints of the *wireless sensor network*.

The Contiki operation system offers two types of communication stacks:

- ✓ uIP : TCP/IP implementation for sensor nodes.
- ✓ Rime : lightweight layered communication stack suitable for wireless communication.

Application in Contiki can use either uIP or Rime and also execute these stacks simultaneously.

The following figure shows the interaction between the two stacks.

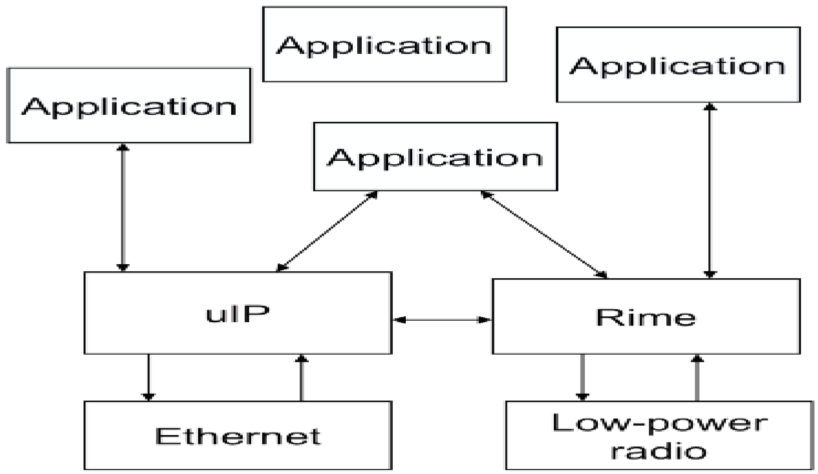

Figure 2. 5 : Communication stacks in Contiki : Rime and uIP

- ***uIP***

Since the wireless sensors networks deploy limited devices in term of memory, processor and energy consumption, the Integration of traditional services must this fact into account which is respected in the TCP/IP implementation for the sensor nodes.

The uIP, also called micro IP, is designed to integrate the minimum required features of the TCP/IP stack with several protocols such as UDP,TCP, ICMP and IP protocols.

The memory management in uIP is characterized by using a single global buffer containing the message with a maximum size of one packet. Hence , the application acting by responding or copying the data must be immediate to avoid the overwriting that may be done on the next incoming packet.

- ***Rime***

Rime is a lightweight layer communication stack designed for WSN. The simplicity of the implementation is one of the purpose of this stack. Comparing to the traditional layered architecture, Rime offers better memory management with less than 10 kilos bytes for the code footprint and an order of tens of bytes as data memory requirements.

Rime is organized in layers presenting several wireless network protocols as shown in the following figure.

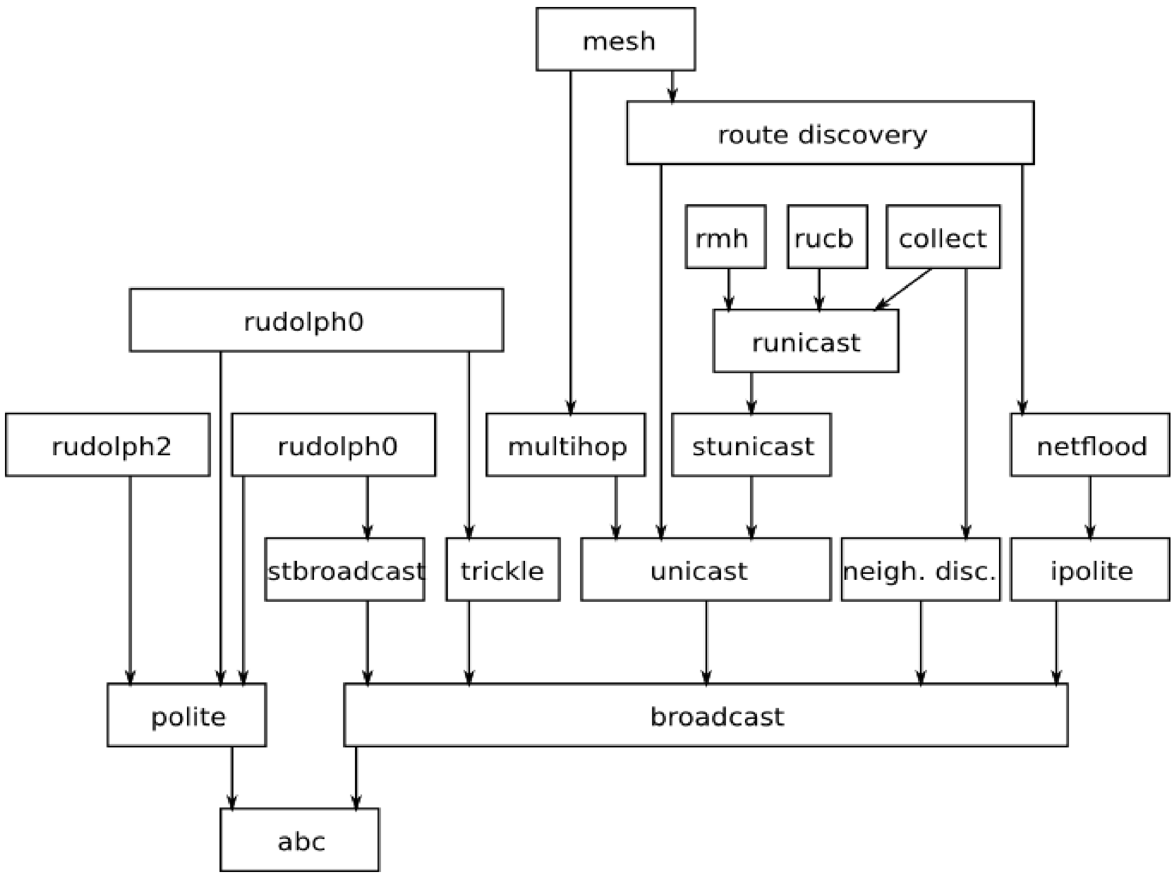

Figure 2. 6 : Rime protocols

Hence, Rime permits to reduce the complexity of protocol implementation by splitting this implementation into several layers e. g the netflood protocol is implemented with Rime primitives ipolite, broadcast and abc.

The lowest level primitive in Rime is anonymous broadcast abc .It does not provide a node addressing that will be added by the upper primitive.

2.1.3. MAC layers in Contiki

The purpose of ameliorating the mac layer efficiency is basically related to aim to reduce the performance of lower power networks in term of energy consumption and reducing the interference effect. Contiki designed for WSN has integrated several MAC protocols permitting to avoid collision and reduce the packet redundancy are classified into categories:

- ✓ Sender-initiated protocols: The sender initiates the packet transmission operation by sending short control packets called RTS (request to send). A correct packet reception is indicated by receiving a positive acknowledgment.
- ✓ Receiver-initiated protocols: The receiver initiates the operation by sending a request-to-receive control packet RTR. Meanwhile, the sender keeps sending data packets until it receives a negative acknowledgment. In this case, it transmits the required data packet.

Avoiding the contention is done in Contiki MAC layer by several sender or received initiated protocols such as NULLMAC, LPP and LPL protocols.

a. NULLMAC

NULLMAC is a simplistic MAC protocols that that reduce the complexity of packet exchange among the network by maintaining the radio always awake. This protocol permit to increase the rate of packet received without redundancy but it does not provide power saving mechanism.

b. LPP

Lower Power Probing is a receiver-initiated MAC protocol. It is characterized by sending RTR packet, also called probes , by the receiver announcing that is awake and ready to receive data packets. Sending probes is followed by a listening time in which the sender may turn its radio on and receives the RTR. In this case, it triggers the data packet transmitting.

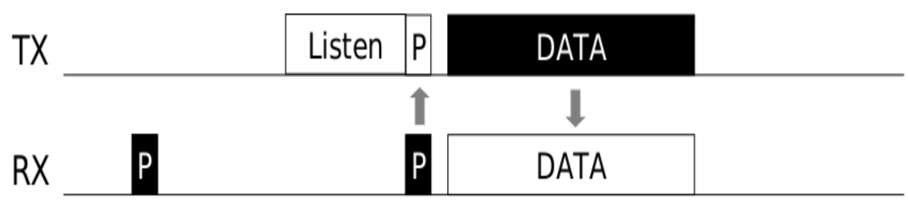

Figure 2. 7 : LPP protocol

c. LPL

In the Lower power listening, the sender keeps transmitting data packets until the receiver wakes up and detects packet transmitting and send back an acknowledgment packet in case of receiving full message.

The ContikiMAC is a lower power listening protocol implemented in Contiki using repeatedly wake-up period in the receiver side and a repeatedly sending packet until receiving an acknowledgment in the sender side.

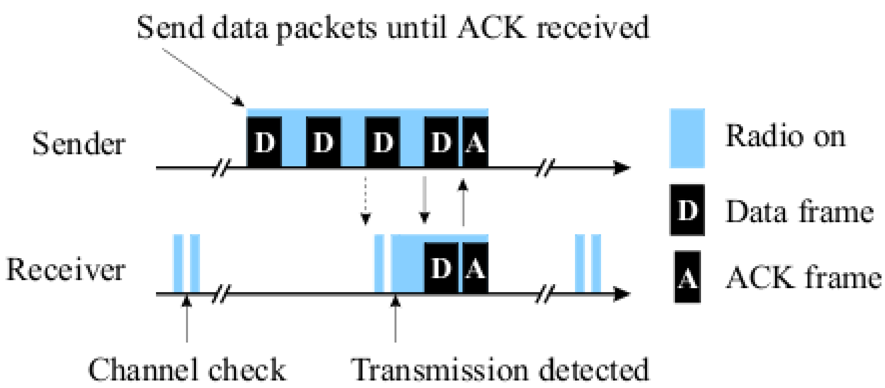

Figure 2. 8 : LPL protocol

d. X-MAC

X-MAC is sender-initiated protocol characterized by its power efficiency and its high throughput .The sender initiates the transmission operation by sending short message called strobes in order to wake up the receiver that reduce the listening time and turn the radio on on for short regular period to listen to the strobes. Receiving a strobe to it make the the receiver wake up and reply by an acknowledgment announcing that it is ready to receive the data packet that would be transmitting by the sender. The figure() show the X-MAC protocol timeline.

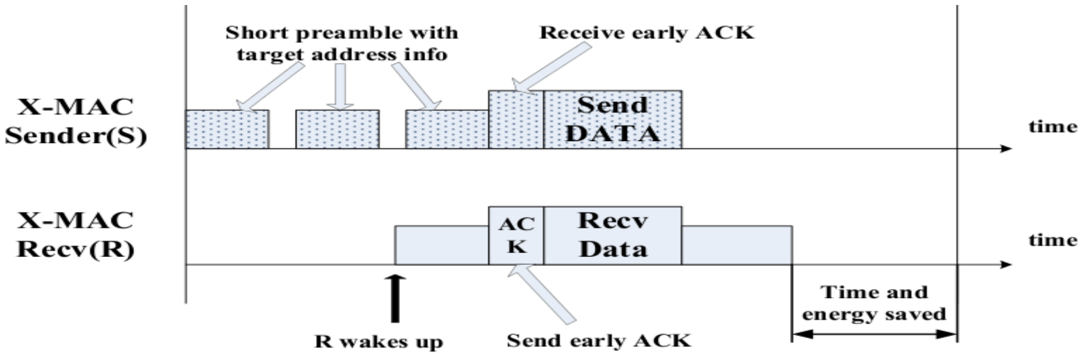

Figure 2. 9 : X-MAC Time Line

2.1.4. Contiki Simulator: Cooja

The Contiki operating system uses Cooja **[5]** to execute the sensor nodes and to control its performance. Cooja permit s to compile the Contiki code for simultaneous simulation for the network devices that may represent different kinds or using different applications.

Cooja loads the compiled Contiki programs into Java using Java Native Interfaces (JNI) and operates at three different levels:

- ✓ ***Networking Level*** : by supporting the different routing and duty cycles protocols implemented in Contiki
- ✓ ***Operating System Level*** : by executing native operating system and simulating different processes
- ✓ ***Machine Code Instruction Set Level***: by deploying nodes with different underlying structure than the typical nodes.

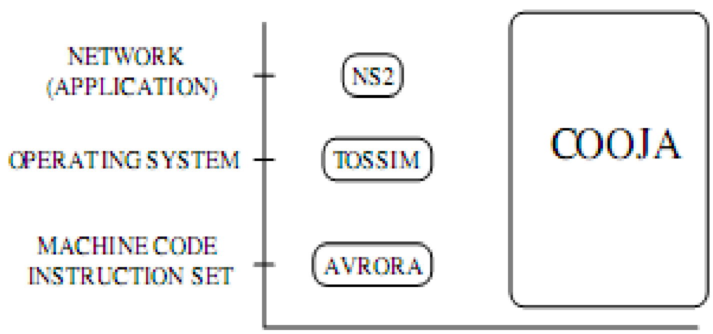

Figure 2. 10 : Simultaneous Simulation with Cooja

The simulation environment in Cooja offers many interfaces and plugins permitting to run the contiki codes by creating the nodes type and display the functioning of the different layers of the nodes such as the MAC , RDC and the routing protocols.

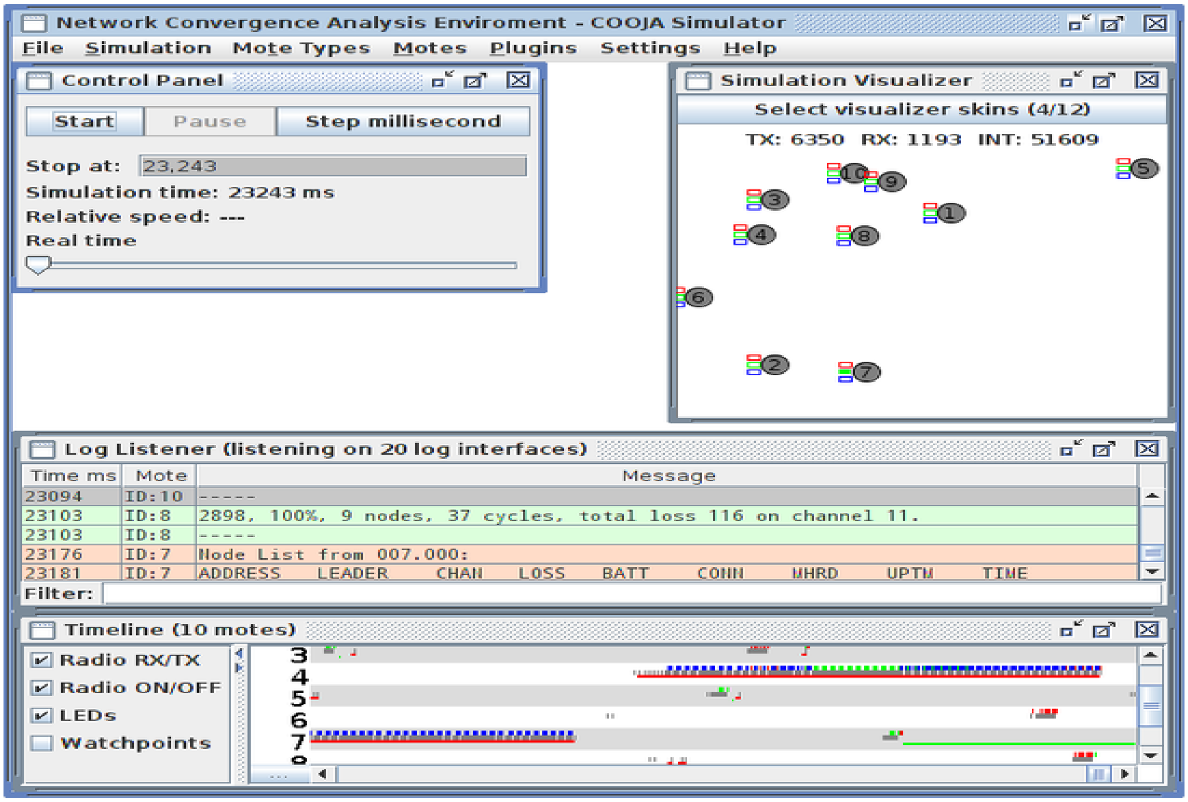

Figure 2. 11 : Cooja Interface

The Cooja interface consists of:

- The control panel that permits to set the simulation time parameters mainly the simulation speed.
- The simulation visualizer that allows to handle the motes with a list of option on the node such as the coffee file system, the LEDs, the button
- The log listener that shows text output of the nodes identified by the time and the mote ID.
- The timeline that displays the different physical state of the node (transmitting receiving radio on/off) as a function of time.

2.1.5. Database

A sensor network database allows to collecting the physical measurement and provides an interaction with the user or any external device to extract to data collected using queries.

This type of database should take into account the constraints in WSN basically the limited capacity of storage and the cost of communication in term of energy during the query execution.

To deploy a sensor network data base, two approaches are proposed :

- *Centralized approach*: storing the data collected from the nodes in external device connected to the network via a gateway.
  In this case the queering processing is done with the centralized database that offers better performance concerning the memory capacity
- *Distributed approach*: storing the data within the network and using the queering process with an in-network way.

In this section we present briefly two sensor database systems.

a. TinyDB

TinyDB is distributed sensor database system providing a query processing on the sink node using the basic language feature in SQL such as CREATE,SELECT, JOIN

The following figure illustrates the query processing through a sensor network:

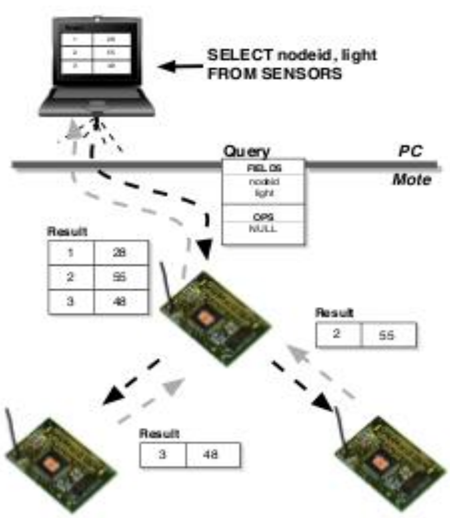

Figure 2. 12 : Query precessing in TinyDB

b. Antelope

Antelope is database system designed to fit the sensor with constrained resources offering to each node the opportunity to run and manage its own database system. The antelope architecture is composed by 8 elements:

- query process : parses the AQL query
- privacy control : guarantees that the query is correct
- Logic VM : executes the queries
- database kernel : manage the database logic
- index abstraction : manage the indexing logic
- indexer process : builds the indexes
- storage abstraction : holds the storage logic
- result transformer : presents the query results in a readable way

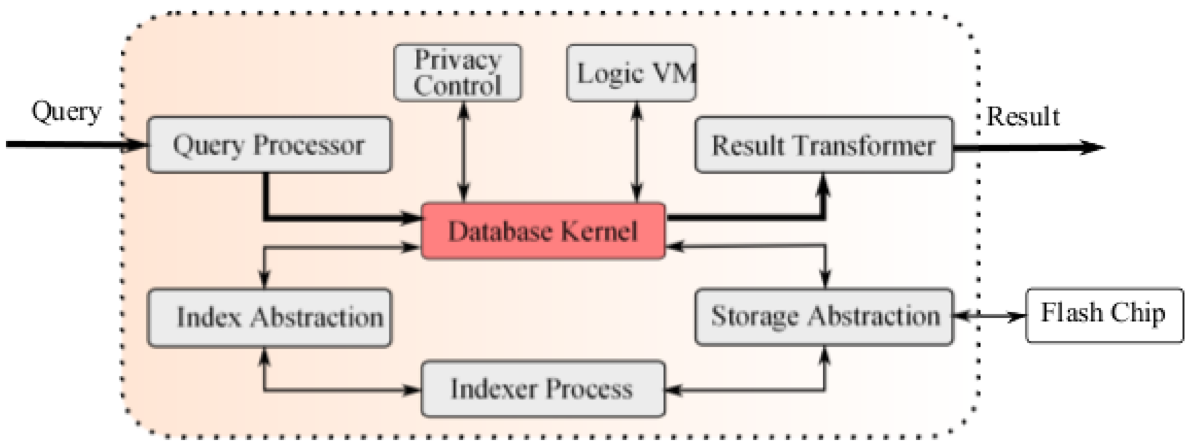

Figure 2. 13 : Antelope Architecture

Antelope is recently implemented in C programming language and integrated in the Contiki operating system offering an efficiency in energy consumption and in execution time.

2.2. Experiment design

2.2.1. Experiment goal

The purpose of the experiment is to better understand real-world connectivity and interference scenarios in low-power wireless networks.

We represented previously several theoretical and physical connectivity models that characterize the transmission through a given network.

These models are limited in term of taking into account the physical parameters of the conditions of the network environment. Thus our motivation is to overcome those limitations and design an experiment permitting to deploy a real scenario of wireless network with large number of sensor nodes and collect the data concerning the transmission quality (channel quality, received signal strength, link quality indicator) in order to maximize the spatial reuse of the spectrum in adaptive low-power wireless networks.

2.2.2. Experiment approach

In order to establish our experiment design we need first to define to determine the physical parameters that should be measured to describe the connectivity through the wireless sensors network.

This experiment is designed to explore real-world channel properties in indoor environments with ~~of~~ IEEE 802.15.4 radios. It is based on broadcast transmissions, using TelosB sensor nodes to scan the sixteen IEEE 802.15.4 channels with twenty nine different power level.

Therefore we consider two types of nodes:

- ***Sender node***

Its function is to send packets on different channels with several transmission power levels. The sender node behaves as follows:

- ✓ Send a broadcast message in a channel reserved for network control purposes. This message contains the data channel in which probe messages will be send to all receiver nodes. We call this message a beacon. Beacons are sent with maximum power to ensure its reception. The control channel would be chosen between 16 channels with the minimum level of noise and interference.
- ✓ Wait for a period of time that allows the receiver nodes to change to the data channel and compute the Channel Quality (CQ) metric **[6]**.
- ✓ Send probes with different transmission powers and return to the control channel.

➢ ***Receiver node***

The main role of receiver nodes in this experiment is to compute the CQ metric and store the signal strength (RSSI) and link quality (LQI) attributes of each probe packet received. Its behaviour consists of the following states:

- ✓ Create a set of tables to store the channel and link parameters measured. We use the Antelope RDBMS **[7]** to create and manage these tables in the mote flash memory.
- ✓ Upon reception of a beacon, switch to the data channel indicated in it.
- ✓ Measure and store the RSSI values with run-length encoding.
- ✓ Listen to the sequence of the probe packets and temporally store the RSSI and the LQI values in an array in RAM.
- ✓ Store the values in the corresponding tables in the database.
- ✓ return to the control channel to listen for the next beacon.

Each mote will be connected to an *usb* power adapter to provide continuous power supply and we will use the Telosb user button to interact with the respective programs. At the end of the process the data will be extracted from the receiver nodes and stored in a laptop hard disk drive to be analysed later.

2.2.3. Measured parameters

➢ ***RSSI***

The *Received Signal Strength* is reliable metric in telecommunication systems and mainly in wireless senor network. It indicated the power level of the received radio signal.

Understanding the *RSSI* variation depending on the transmission power of the sender and the channel contributes on evaluate the network behavior and adjust the transmission parameters.

Theoretically, the *RSSI* values increase with the transmitter power:

RSSI (dB) =10* log (SWP * SXG * RXG *$(\lambda/4\pi d)^2$/RFP); where:

SXP: sender transmission power

SXG: sender gain

RXG: receiver gain

λ: wave length

d:distance between sender and receiver

RFP: reference power (1mW).

- ***Link Quality Indicator***

Link quality indicator is metric introduced in wireless sensor network to measure the error in the modulation of the received packets.

- ***Channel quality***

The channel quality is a metric proposed to determine the availability of the channel over time . It considers the values of the receiver signal strength indicator (RSSI) measured periodically with period P. We suppose CV the channel vacancy where the value of RSSI is higher than a given an acceptable noise and interference threshold Rthr. Thus, the channel is considered as idle in case of RSSI < Rthr.

Let mj be the number of CV consisting of j consecutive idle sample and n the total number of sample.
We define the channel quality metric as:

$$CQ(\tau) = \frac{1}{(n-1)} \sum_{j|(j-1)P>\tau} j^{(1+\beta)} m_j$$

Where $\beta > 0$ is the bias and $\tau > 2P$ is the time window of interest (the duration of packets).
The larger values of CQ corresponds to the better channel to deploy.

2.2.4. Sequence diagram

The experiment design can be described on the following sequence diagram detailing the packets transmission between the sender and the receiver on one hand and the measurement and the storing process within the receiver node.

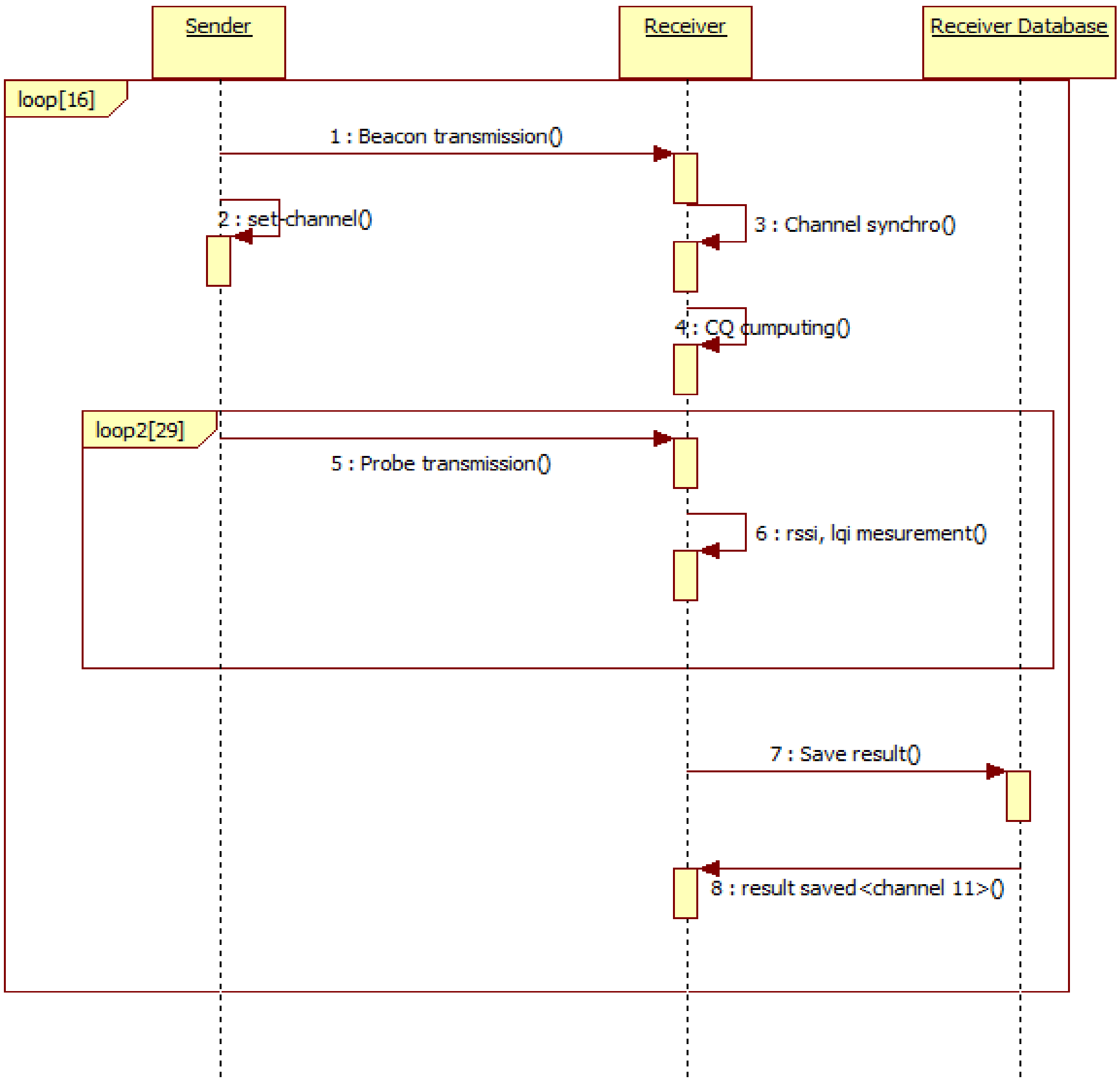

Figure 2. 14 : Sequence diagram

2.2.5. Experiment time line

Our experiment is based on deploying nodes operating in two principal modes : sender and receiver using different channels ,power level and memory resources for several operations (computing , measuring , storing, creating and populating the data base) . In this case, the time is required for this change of state to access to memory is an important figure of merit.

The time synchronization between the sender and the receiver is determined by several factors:

- scanning the channel and sampling the RSSI values once a beacon is received
- measuring the RSSI and the LQI values and storing into an array for each probe received
- creating and populating the database tables: These tables will be stored in the Coffee file system which should be taken into account due to the long read and write access delays of flash memory.

The following figure shows the predictable execution time for the different data base operations in Antelope.

- The propagation delay between neighbouring nodes is negligible; e.g A distance of 30 m needs 10−7 s for speed of light c ≈ 300.000.000 m/s.

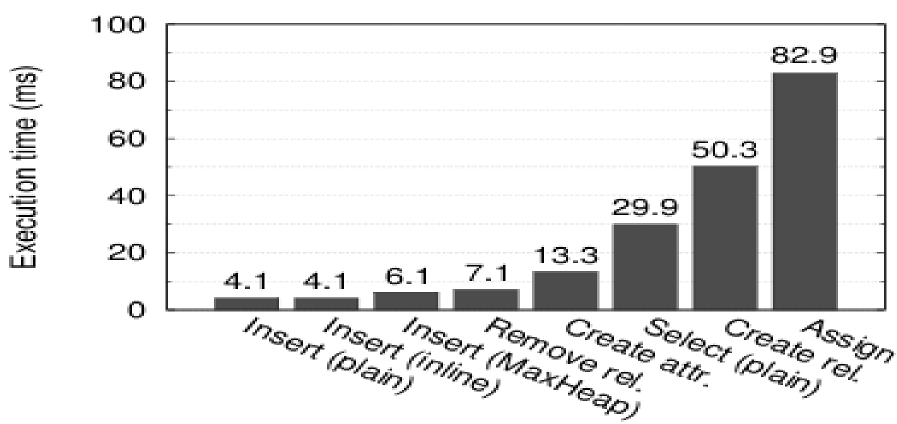

Figure 2. 15 : Micro-benchmark of the main classes of operations in Antelope.

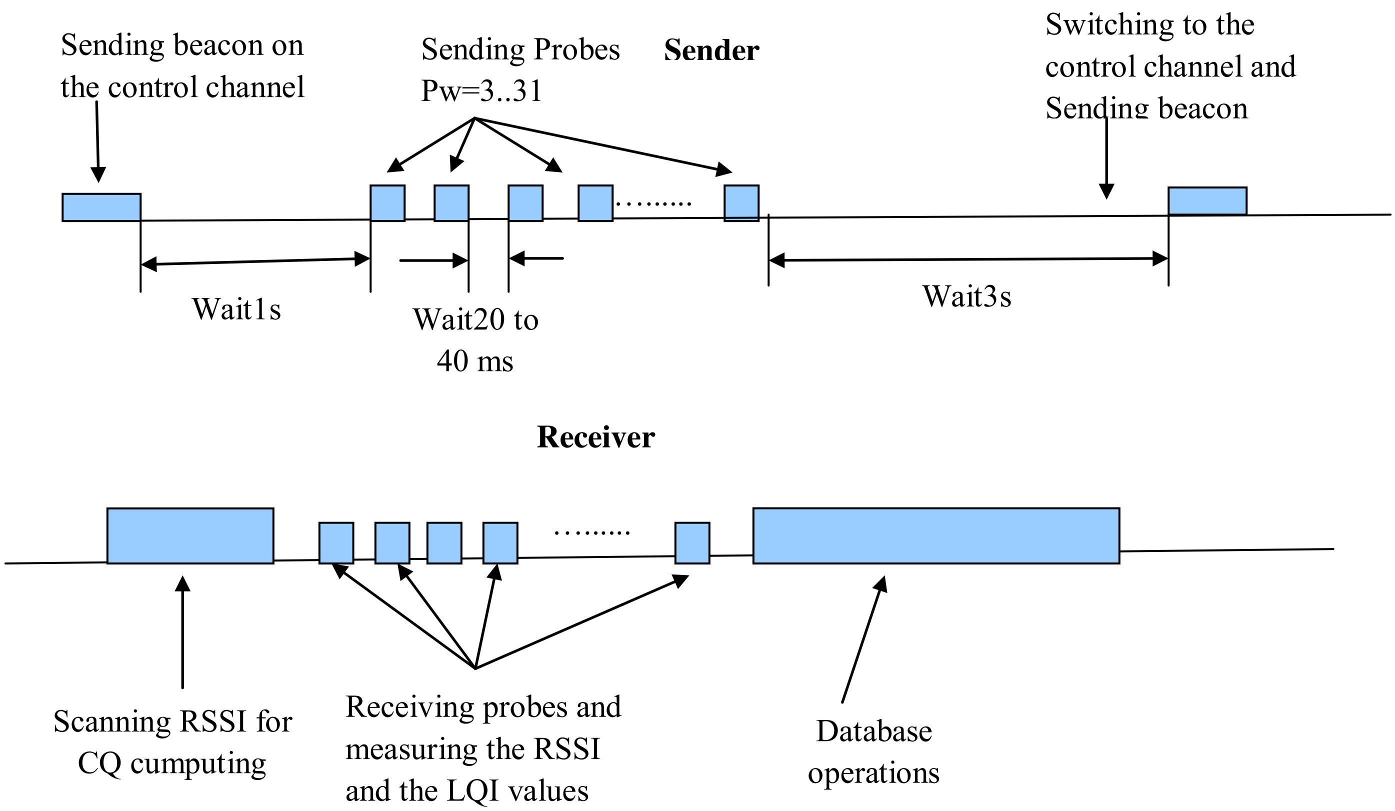

Figure 2. 16 : Experiment Timeline

2.3. Implementation

In this subsection we represent our approach of measurement and we define the function of each component and the processes implemented in the network designed to be deployed in real scenario taking into account the devises constraints in energy and mainly in memory and the experiment progress in time.

The experiment designed is based on four processes determining the functions of different parts of the network and its interaction. The following class diagram offers an overview of the experiment design.

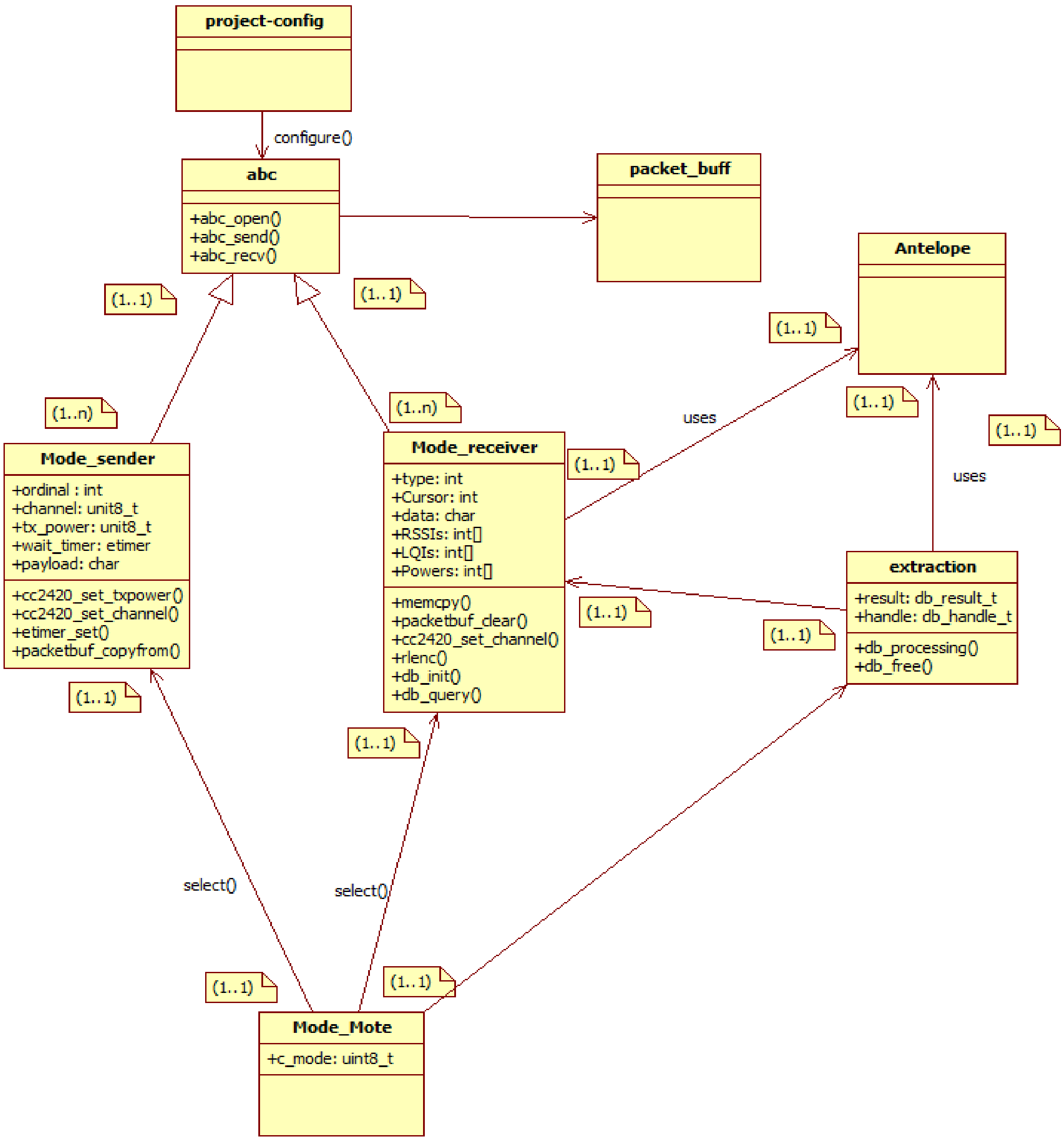

Figure 2. 17 : Class Diagram

The classes use the project-conf class permitting to configure the Tmote sky platform. This configuration concerns the network parameters essentially the MAC protocol, the RDC protocol, the radio driver, etc.

To avoid complexity in transmission and to increase the throughput, we use the nullmac_driver and nullrdc_driver to keep the radio_on during the process.

A Part of the projet-config is illustrated on the figure 2.18.

```
#undef QUEUEBUF_CONF_NUM
#define QUEUEBUF_CONF_NUM                       4

#undef NETSTACK_CONF_RDC
#define NETSTACK_CONF_RDC                       nullrdc_driver

#undef NETSTACK_CONF_MAC
#define NETSTACK_CONF_MAC                       nullmac_driver

#undef NETSTACK_CONF_RDC_CHANNEL_CHECK_RATE
#define NETSTACK_CONF_RDC_CHANNEL_CHECK_RATE 4

#undef DCOSYNC_CONF_ENABLED
#define DCOSYNC_CONF_ENABLED                    0

#undef DB_FEATURE_JOIN
#define DB_FEATURE_JOIN                         0

#undef RF_CHANNEL
#define RF_CHANNEL                              16

#undef ROUTE_CONF_DEFAULT_LIFETIME
#define ROUTE_CONF_DEFAULT_LIFETIME             300
```

Figure 2. 18 : Project-config

The radio driver configuration in our project in CC2420-driver which defines the CC2420 functioning as a hardware operating on the 2.4 GHz ISM band. It allows managing packets, data buffers and linking quality indication which will be useful.

The principal functionalities of the nodes are implemented in the following classes : Mode_sender,Mode_receiver and Mode_extraction.

The first two classes are specialized from the abc class that represent a Rime primitive used to send packets in a local area with an anonymous broadcast.

This classes uses basically three functions :

- *abc_open*: to set up an anonymous broadcast connection on given channel
- *abc_send*: to send an anonymous broadcast packet stored in the packet buffer
- *abc_close*: to close an abc connection previously opened with abc_open().

2.3.1. The sending process

In the transmitting process, the sender_node class was designed to interact with the other nodes by sending two types of packets

- *beacon* : containing the data channel and sent with maximum power
- *probes* : sent in different channels and with different power level

The following figure illustrates the sending process:

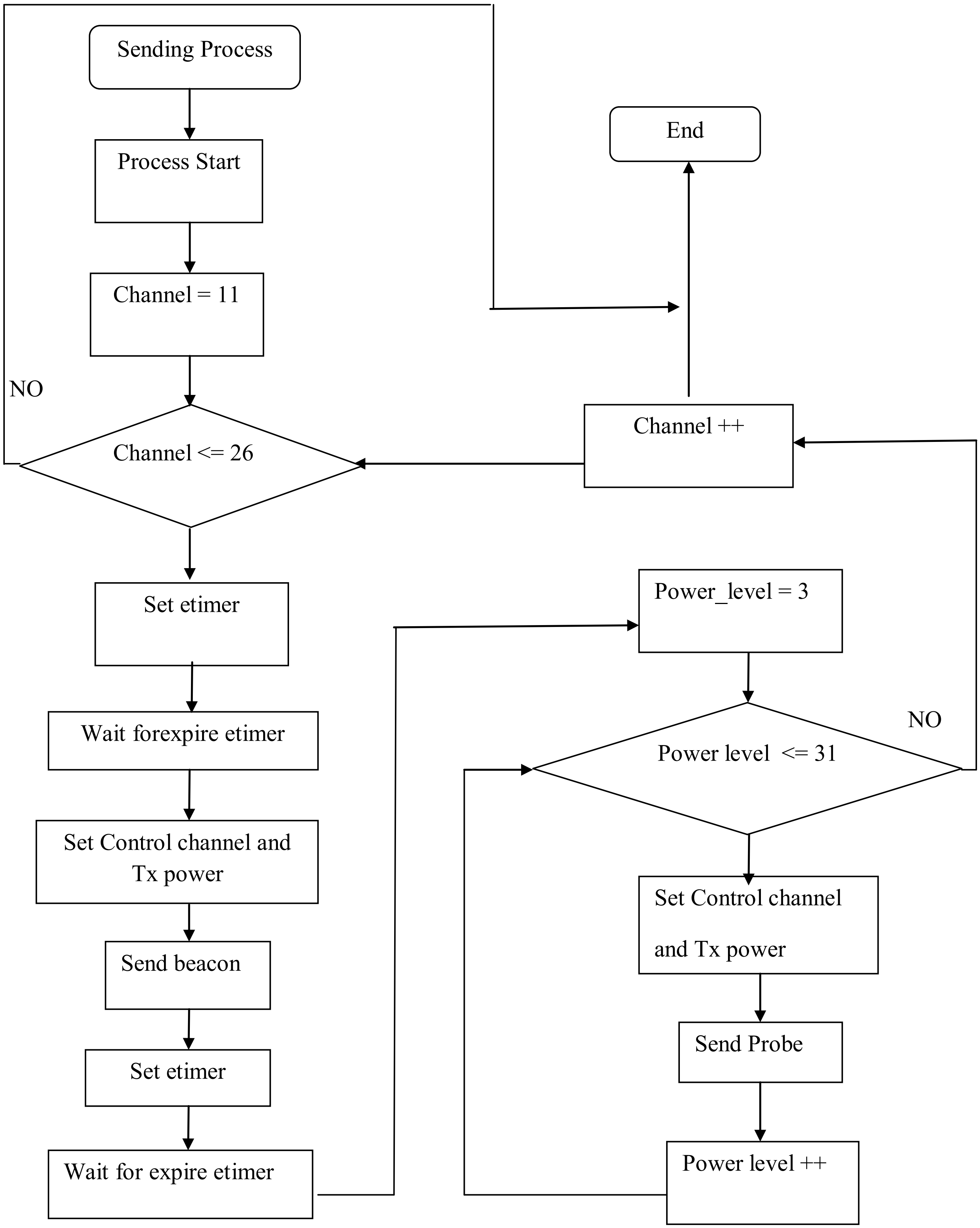

Figure 2. 19 : Sending Process Chart

The first step in the sending process is to construct the beacon packet that consists of three parts: the ordinal, the channel and the power. The first part is used to define the rank of the beacon. The channel and the power are defined using the functions **cc2420_set_channel()** and **cc2420_set_txpower()** taking as attributes **CONTROL_CHANNEL** and **CC2420_TXPOWER_MAX** .

This data is will be copied to the buffer stack with **packetbuf_copyfrom()** and sent involving the **abc_send()** function.

Sending a beacon will be followed switching to the data Channel and setting the etimer which is active timer defined in Contiki and used to trigger an event when it expire. This event would be starting sending probes with different power level and returning a period to the control channel to prepare the next beacon.

2.3.2 The receiving process

A receiver node would be programmed to measure the channel parameters and to store it in the database using the Antelope functions.

Whenever the receiver node gets the data from the sender, it will invoke the callbacks function automatically. This function is designed to verify first the packet type (see figure 2.21)

- If the packet received is a beacon, the node switch to the channel contained in the packet and defined by the sender and compute the CQ metric using the **rlenc()** function .
- Else, upon a reception of a probe ,The receiver measures the RSSI and the LQI values using the **packetbuf_attr(PACKETBUF_ATTR_RSSI)** and **packetbuf_attr (PACKETBUF_ATTR_LINK_QUALITY)** functions. These values would be temporally stored in the **RSSIs[ ]** and **LQIs[ ]** tables in the RAM.

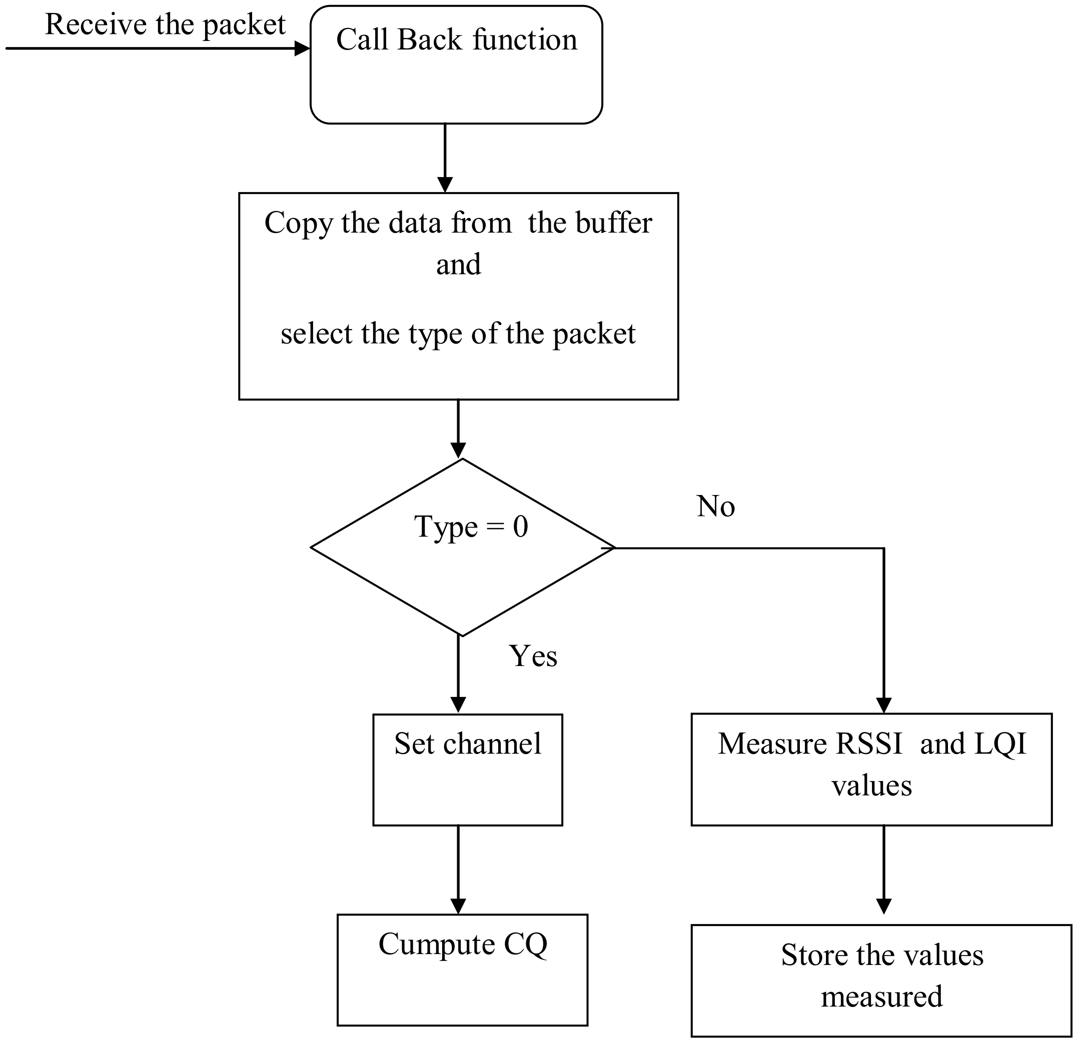

Figure 2. 20 : The callbacks function of receiver

2.3.3 Database process

Employing a database in every sensor is one the challenge of our experiment mainly with the memory constraints and the limited storage size. The database in our case will be used to store the measurement and to be queried to extract the data for each channel .Thus, we proposed to employ two types of tables

- ✓ Rx_tables containing the measured values of the RSSI and the LQI for different transmission power and for each channel.
- ✓ CQ_tables containing The RSSI values and its redundancy calculated using the run-length encoding as a form of data compression.

The following figure shows the proposed organization of the database tables:

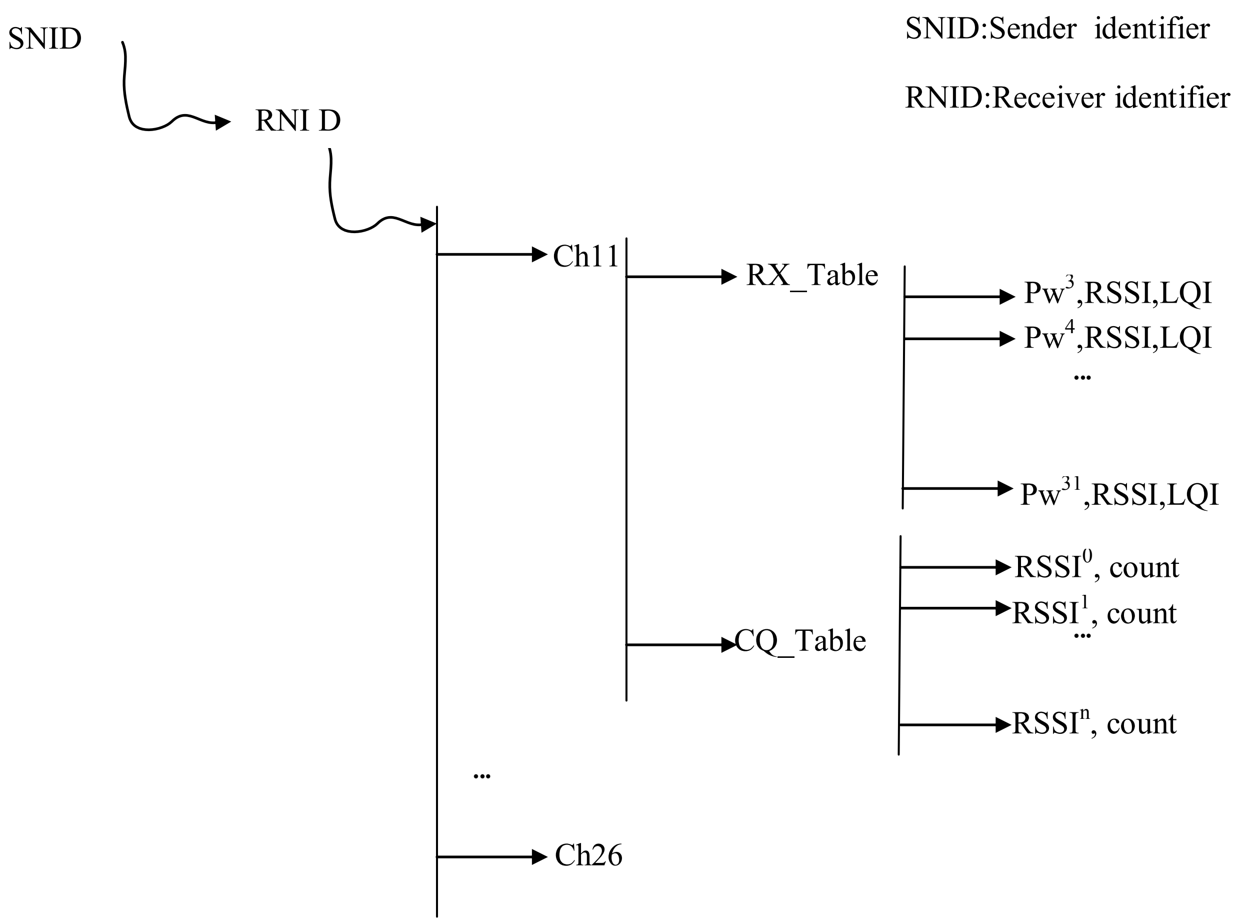

Figure 2. 21 : Database structure

The receiver class deploying the Antelope features mainly its query language called AQL used both to build and to query databases.

The tables are created using a set of relational operations. These operations share generally syntactic elements with SQL but avoiding complex functionality such procedural extensions, triggers, and transactions since AQL is basically designed for systems with modest hardware resources. The following figure shows an example of operations used to define relation and its attributes.

```
db_init();
sprintf(table_name, "Rx");
sprintf(db_create, "CREATE RELATION %s;", table_name);
printf("%s \n",db_create);
sprintf(db_att_power, "CREATE ATTRIBUTE power DOMAIN INT IN %s;", table_name);
printf("%s \n",db_att_power);

sprintf(db_att_rssi, "CREATE ATTRIBUTE RSSI DOMAIN INT IN %s;", table_name);

sprintf(db_att_lqi, "CREATE ATTRIBUTE LQI DOMAIN INT IN %s;", table_name);
sprintf(db_att_chan, "CREATE ATTRIBUTE channel DOMAIN INT IN %s;", table_name);
sprintf(db_att_ord, "CREATE ATTRIBUTE ordinal DOMAIN INT IN %s;", table_name);

db_query(NULL, db_create);
    db_query(NULL, db_att_power);
    db_query(NULL, db_att_rssi);
    db_query(NULL, db_att_lqi);
    db_query(NULL, db_att_chan);
    db_query(NULL, db_att_ord);
    db_query(NULL, "CREATE INDEX %s.power TYPE INLINE;", table_name);
```

Figure 2. 16 :Creating the database table

Conclusion

In this chapter, we have represented the UML language to detail the different features of our experimental approach and its implementation using the Contiki operating system. Testing and evaluating this approach will be the object of the next chapter.

Chapter 3: Tests and Evaluation

Introduction

The next step after designing the experiment is to test the implementation done using the Contiki operating system. We will focus on the behaviour of the nodes and the network using at the beginning the Cooja simulator and deploying after a real-world scenario by establishing a testbed followed by an analysis of our data collected from the experiment.

3.1. Simulation

3.1.1. Compilation

In order to test our implementation we need resort to Contiki simulator Cooja that offers the opportunity to test our implementation for Tmote sky nodes.

Tmote sky is a mote platform used for extremely low power, high data-rate sensor network applications. It has integrated sensors, radio, antenna, microcontroller and programming capabilities.

The main characteristics of the Tmote sky are:

- ✓ 250kbps 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver.
- ✓ Interoperability with other IEEE 802.15.4 devices.
- ✓ 8MHz Texas Instruments MSP430 microcontroller (10k RAM, 48k Flash).
- ✓ Integrated on board antenna with 50m range indoors / 125m range outdoors.
- ✓ Ultra low current consumption.
- ✓ Programming and data collection via USB.

To simulate our code we need compile and upload the program on the Tmote sky platform using the following command: *make TARGET= sky* as shown in the following figure.

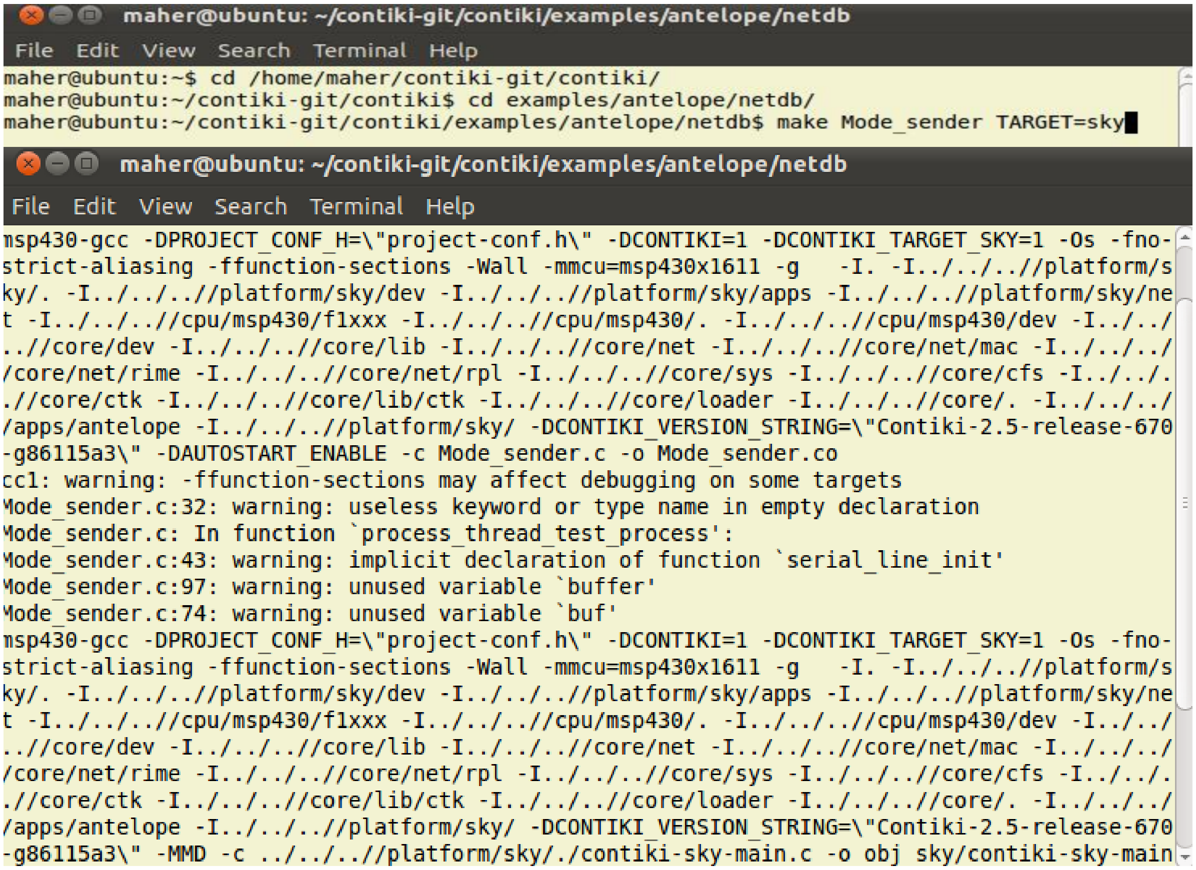

Figure 3. 1 : Program Compilation

3.1.2. Simulation in Cooja

The compiled code would be simulated using the Contiki simulator: Cooja. Cooja supports C language programs as the application design language by employing Java Native Interface (JNI) in order to simulate the software run.

Starting Cooja is done using the following commands:

Cd /contki-git/contiki

cd tools/cooja

ant run

These commands permit to run the simulator Cooja interface and start a new simulation as illustrated in the figure 3.2.

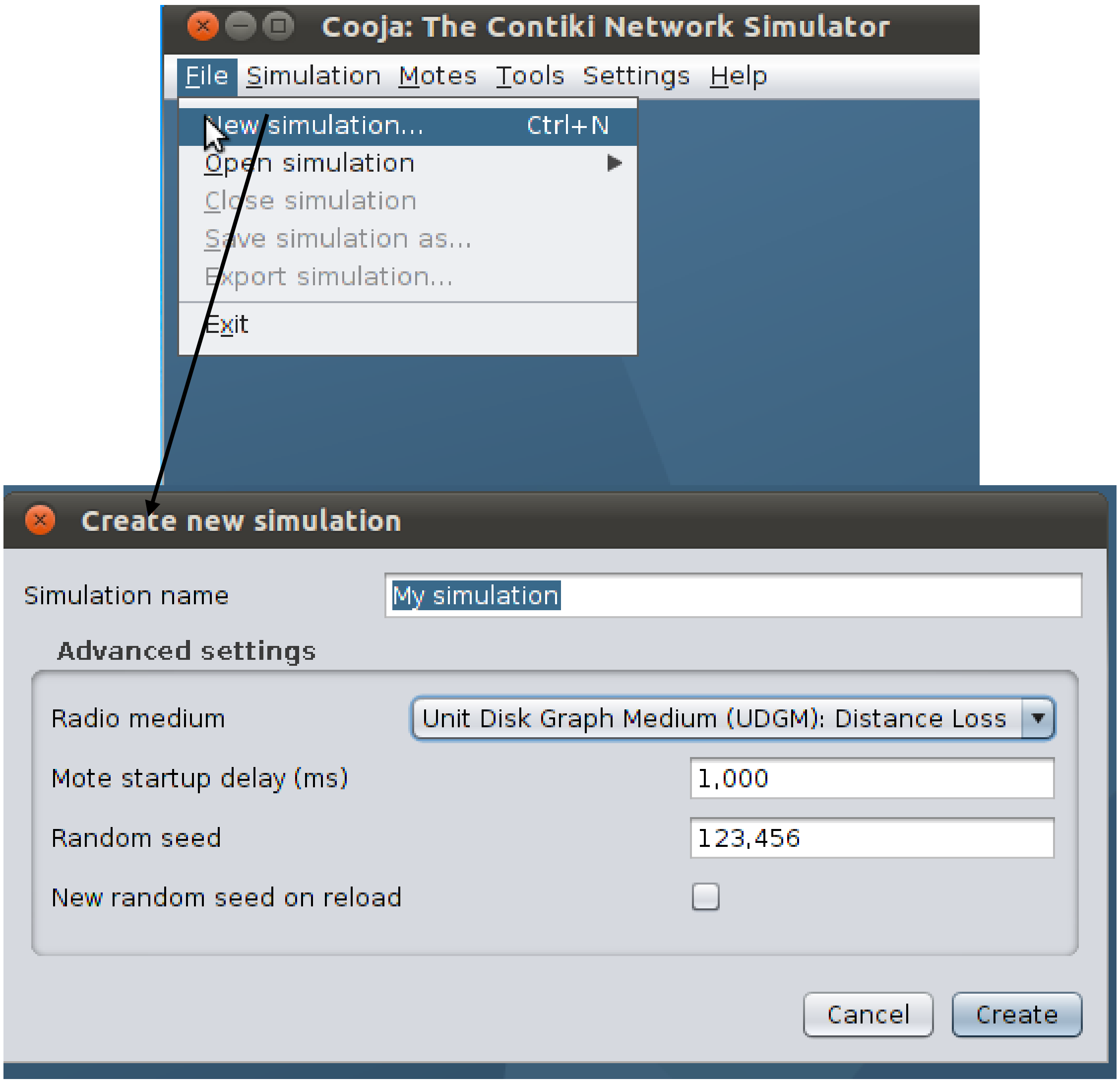

Figure 3. 2 : Create new simulation

In our simulation we choose to employ a simple scenario in Cooja using nodes operating as sender and receiver to test the behaviour of the nodes in term of memory allocation in the Coffee flash system and packet transmission between the nodes.

The simulator Cooja uses the theoretical connectivity model UDG which simplify the transmission aspects of the nodes and divides the radio range into 3 parts :

- an ideal disk modelling the transmission range.
- an interference zone where the packets are lost.
- An out of the radio transmission zone where the nodes are not able to communicate.

In the simulation scenario we consider four nodes: sender and three receivers distributed in different zone; see figure 3.3:

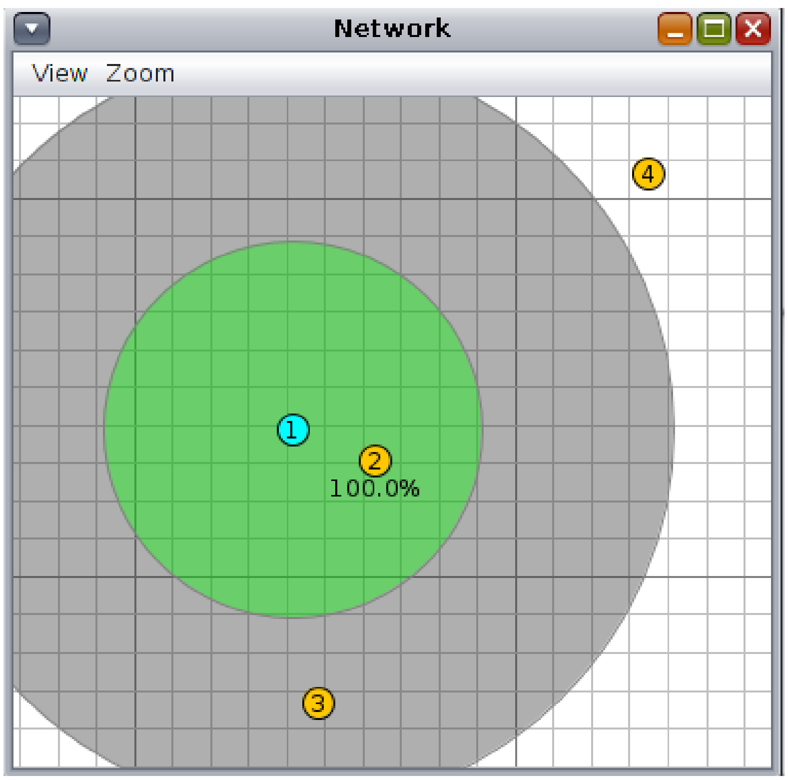

Figure 3. 3 : The Simulation Network

The Node (2) located in the transmission range of the sender node (1) received beacons on the control channel and switch each time to a different channel to listen to the probe and to measure the RSSI and the LQI values.

The following figure illustrates the tables created and populated in the coffee file system (CQ table for each channel + RX table containing the measured parameters).

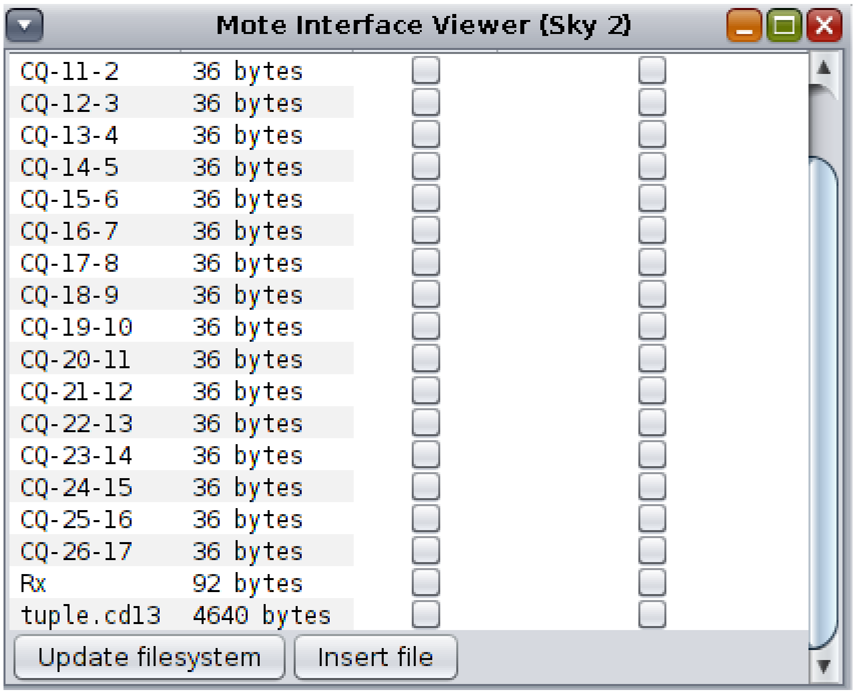

Figure 3. 4 : Tables created int the coffee file system

In term of connectivity the figure 3.5 illustrates the dependency between transmission power and the pathloss. The simulator Cooja considers that the transmissions have the same behaviour regarding the channel used which make the measured values of the RSSI and the LQI depend not on the channel bau only on the transmission power.

As we noticed in the following figure the values of the pathloss decrease with the values of power level between 3 (-25 dBm) and 15 (-7.6 dBm) and have an arbitrary fluctuation for the rest of values which means that the transmission power does not guarantee a better link quality when it grows.

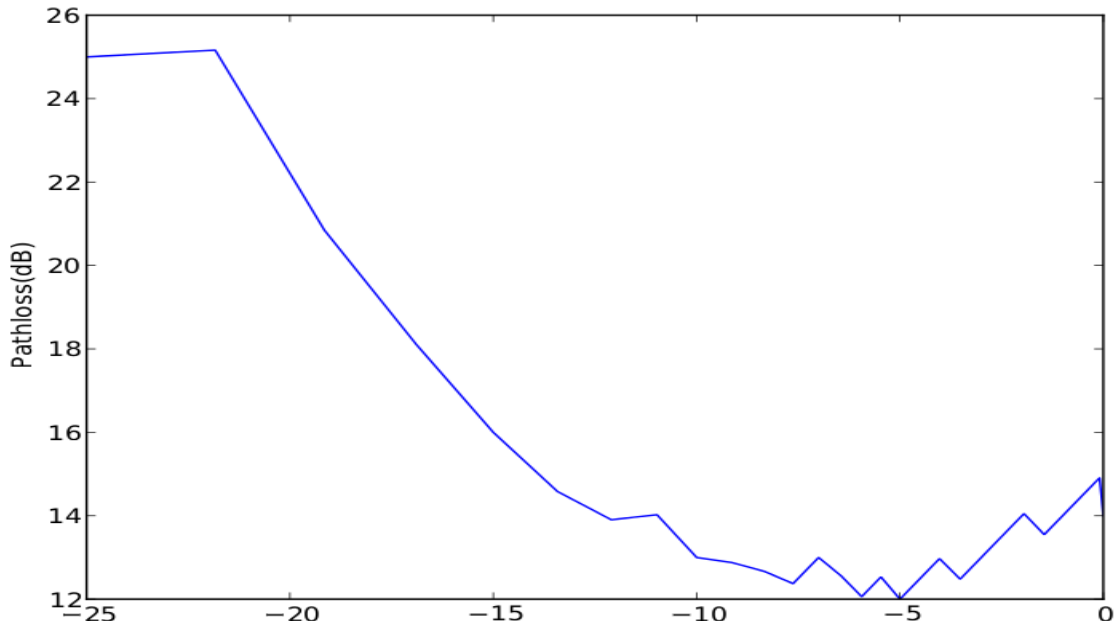

Figure 3. 5 : The Pathloss variation with sender power

3.2. Experiment setup

In order to more understand real-world power and channel for short range radio links through low-power wireless network we need to investigate experimentally our approach. Therefore we consider experimental setup to study the link path between the nodes in the network and how it could be affected by the transmission power and the channel used.

In this subsection we present the experiment features in term of hardware, testbed environment and analysis tools.

3.2.1. Hardware: TelosB Mote

Figure 3. 6 : TelosB Mote

The TelosB mote is an open source platform designed as IEEE 802.15.4 compliant wireless sensor node . The mote offers many features including:

- ✓ IEEE 802.15.4 WSN platform.
- ✓ TI MSP430 Processor, CC2420 RF.
- ✓ Contiki OS Compatible.
- ✓ 2.4 to 2.4835 GHz, a globally compatible ISM band.
- ✓ 8 MHz TI MSP430 microcontroller with 10kB RAM.
- ✓ 1MB external flash for data logging.
- ✓ User & Reset Buttons.
- ✓ 3xLeds.
- ✓ USB Interface.
- ✓ 2xAA Battery Holder.

The Core of the TelosB sensor mote is a TI MSP430 microcontroller. This microcontroller belongs to the Texas Instruments MSP430 family of ultra low power microcontrollers. TelosB has integrated temperature, humidity and light sensors and can be powered either by plugging the USB to a host computer, or by using batteries.

This product is especially suitable not only as a real product to detect the environment, but also as a very useful research platform for developers. Because it has included in the same hardware module all the needed functionalities: sensor readings, processor power and wireless communication potential.

The radio transceiver chip on the board is TI CC2420 . TI CC2420 is a true single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver. It is designed for low power and low voltage wireless applications. CC2420 includes a digital direct sequence spread spectrum baseband modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps. The CC2420 chip allows measuring the received signal strength with an algorithm scale providing values in dBm and using the following equation.

$$P = RSSI_{VAL} + RSSI_{OFFSET} \left[dBm \right]$$

The nominal value of the offset is -45 dBm that we take into consideration when we represent the measurement.

3.2.2. Testbed description

The experiment took place on the one of the first floor of the Cister building representing a realistic indoor environment. We placed a total of 8 nodes in different positions as shown in the figure 3.7:

Figure 3. 7 : Topology showing the placement of the nodes

3.2.3. Tests and evaluation

a. Testing the nodes

The first step of the experiment is to test each node apart in different scenarios to evaluate the signal receiving and to determine the Control channel with the minimum noise and interference. Therefore, we sample the RSSI from the CC2420 transceiver on the sixteen channel of the IEEE 802.15.4. This test permits to determine the control channel used to send the beacon during the experiment.

Testing the motes would be in three situations:

- Motes exposed to the effect of the ambient noise and the external interference coming from the Wi-Fi network.
- Motes placed into an insulator reducing the effect of the external effects.
- Motes exposed to the effect of interferer motes operating on 3 different channels (12,18,24).

The following figures shows the results of sampling 2346 RSSI values in approximately 55 ms. We took three values to represent: the maximum, the minimum and the average.

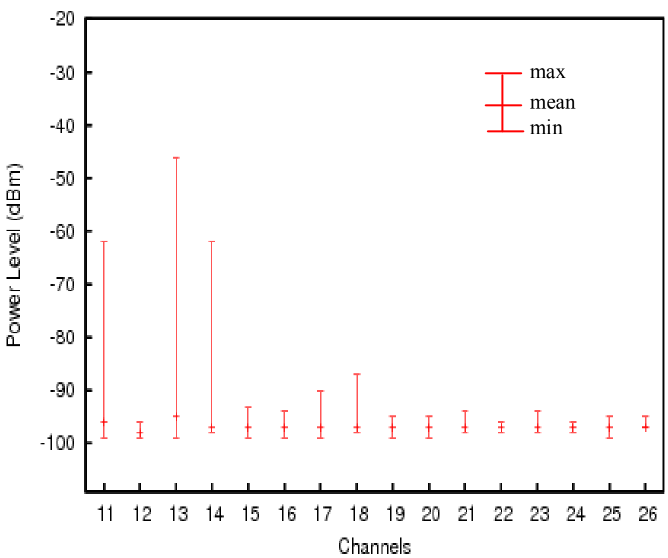

Figure 3. 8.a : First situation (with external effects)

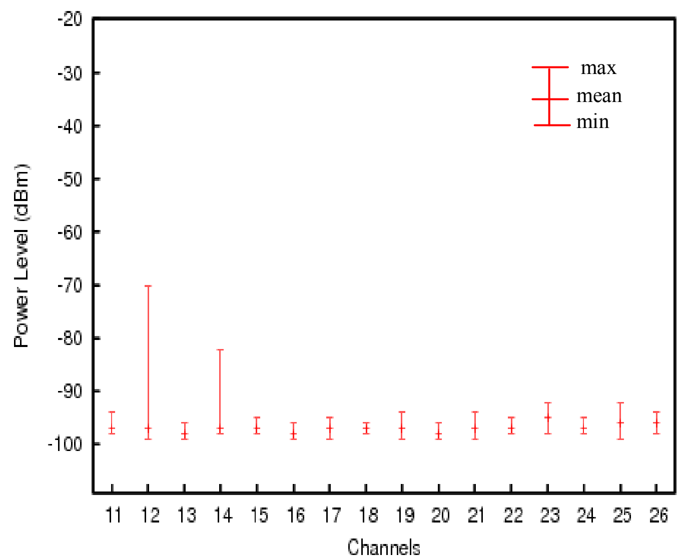

Figure 3. 9.b :Second situation(with an insulator)

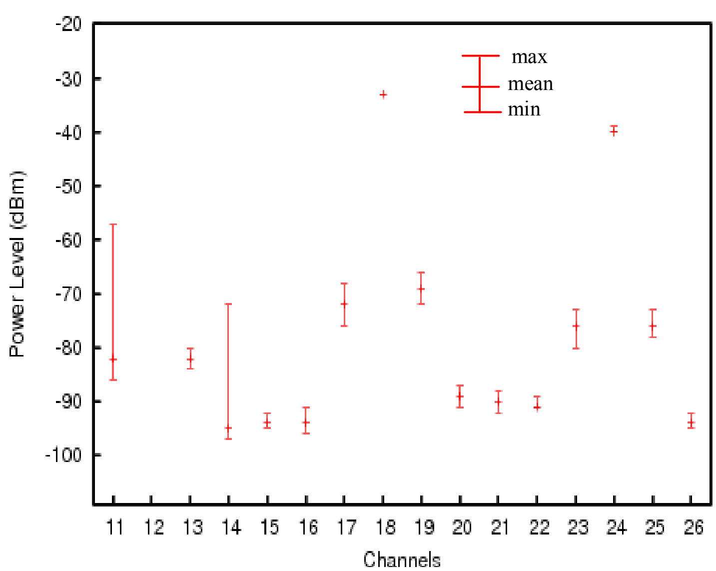

Figure 3. 10.c : Third situation (with interference)

The figures (3.8.a) shows that the channels (11,13,14) are more affected to the external effects related basically to ambient noise or the interference with other devices in the room essentially the Wi-Fi.

The Figure (3.8.b) illustrating the result of the RSSI measurement inside an insulator shows that the cause of a misbehaviour cannot only be related to the external effects but also to the devise itself mainly the hardware component basically the radio transceiver.

The figure (3.8.c) depicts measured RRSI values in case of presence of interferes emitting signals in three different channels (12,18,24). The results show that interference not only affect the transmission in these channels but also in the close channels e.g the transmission in channel 24 affects the channels 23 and 25 illustrating a signal of -75 dBm.

The result of this test using different motes permitted to:

- Select the motes that could be used for the experiment.
- Determine the control channel presenting the minimum amount of noise and less affected by interference.

b. Experiment results

- ***Link behaviour***

To represent the result of our experiment we developed a script written in python permit to read the results stored in text files, extract the RSSI and the LQI values and draw figures representing the variation of those parameters with the transmitting power in different channels. The following figures show the pathloss and the LQI values for the link between the nodes (1) and (2) in channels 16 and 26.

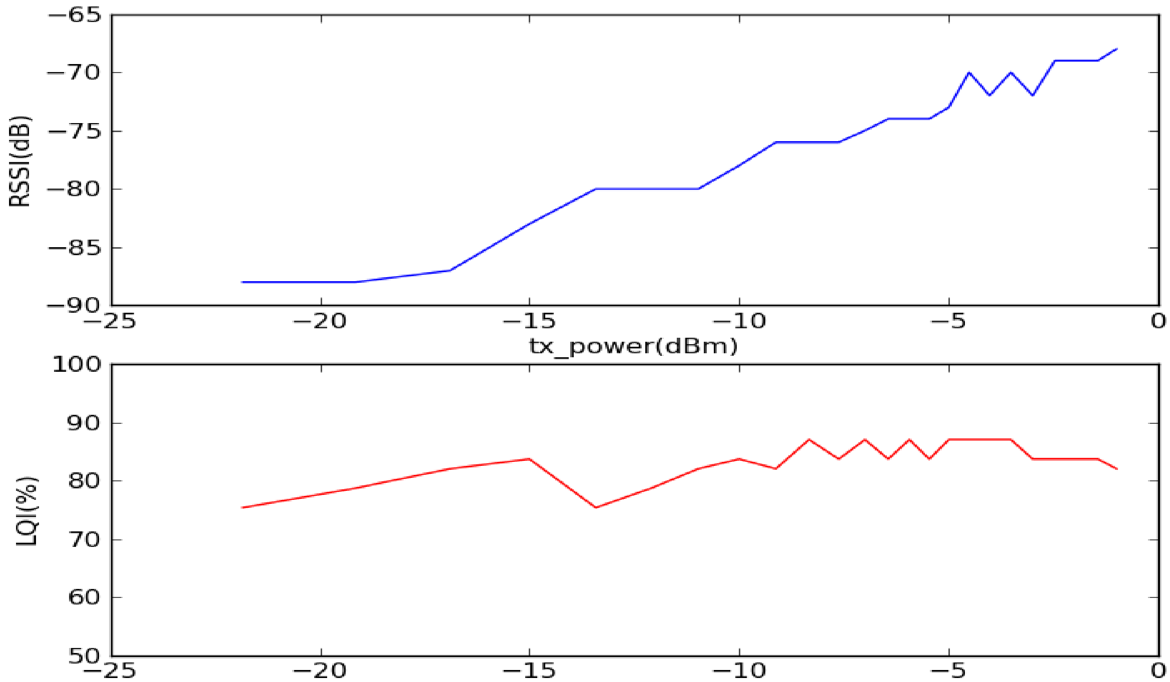

Figure 3. 12.a : Link 1-2 in channel 16

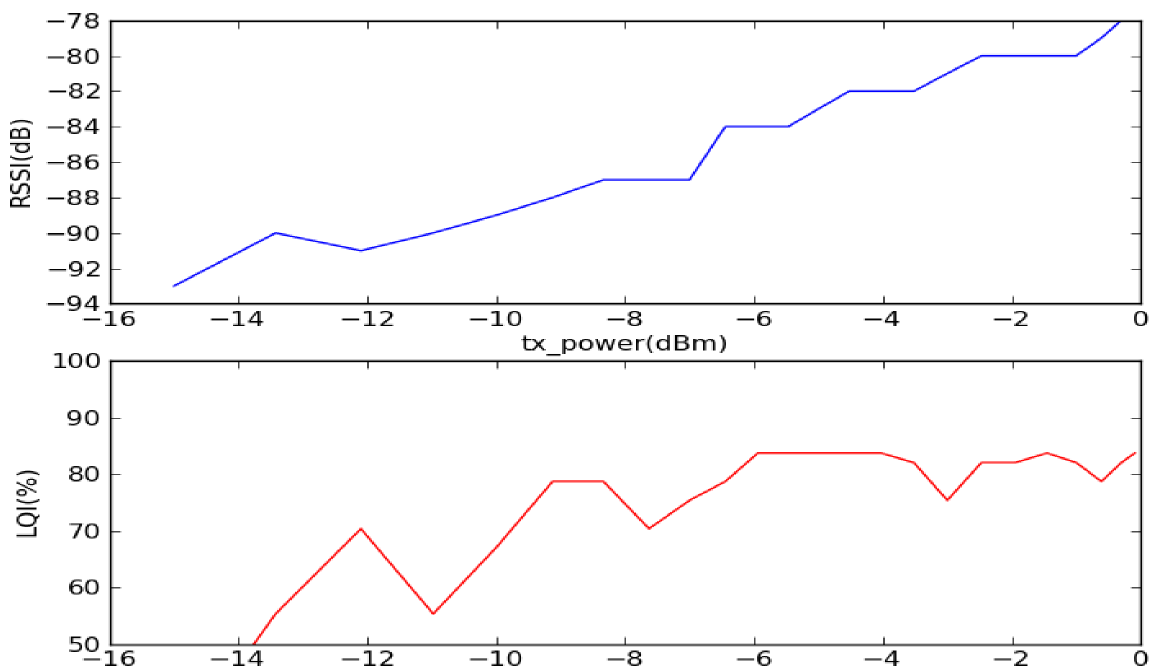

Figure 3. 11.b : Link 1-2 in channel 26

The RSSI measured for the same link in different channels varies between -90 dBm and -68 dBm in channel 16 and between -94 dBm and -78 dBm in channel 26 . Noticing also that packets transmitted in low power may or may not be received successfully e.g packets transmitted with power levels 4,5 and 6 were not received in channel 26 which not the case in channel 16 . Hence, changing the frequency in wireless sensor transmissions contributes to significant changes on the measured RSSI.

The values of Link Quality Indicator LQI shows that channel has an unpredictable effect on the link behaviour: the LQI varies between 70% and 90% in channel16 and between 50% and 85% in channel 26 for power levels between 7 and 31 . This means that designing protocols relying on frequency hopping must take into account the variation of the signal strength.

The figures 3.9.a and 3.9.b shows also that the transmission power has a linear effect on the measured RSSI. Therefore, we conclude that the signal received increases proportionally with the transmission power.

- ***Network graph***

Modelling a network using a graph is needed to describe the connectivity between its components to give a global view of the links quality i.e The network can be viewed as a communication graph, where sensor nodes act as the vertices and a communication path between any two nodes signifies an edge.

To analyses the result of our experiment we use a python code permitting to draw the network graph based on data collected to describe how the power level can affect the connectivity in the network .The input of this script is values measured that should be converted to an edge showing the link quality between the motes.

The following figures show the network graph drawing in different power levels and presenting the pathloss as the weight of the links between the motes:

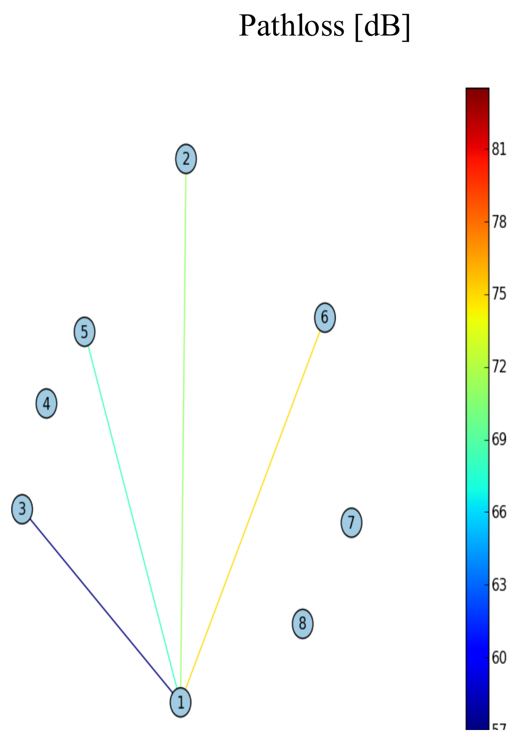

Figure 3. 14.a : Network graph (power level=7)

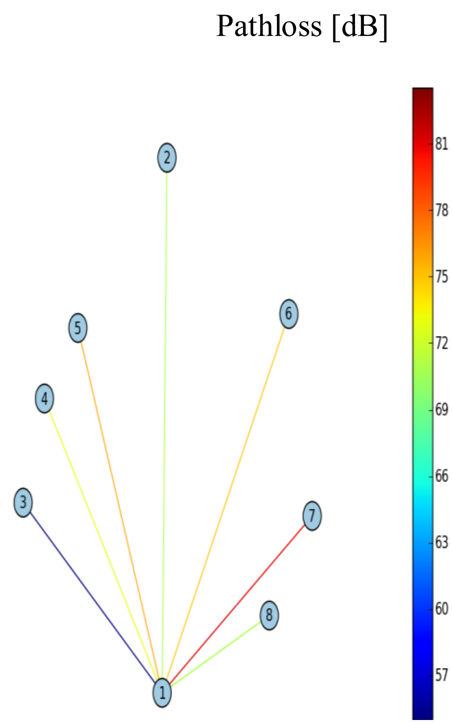

Figure 3. 13.b : Network graph (power level=15)

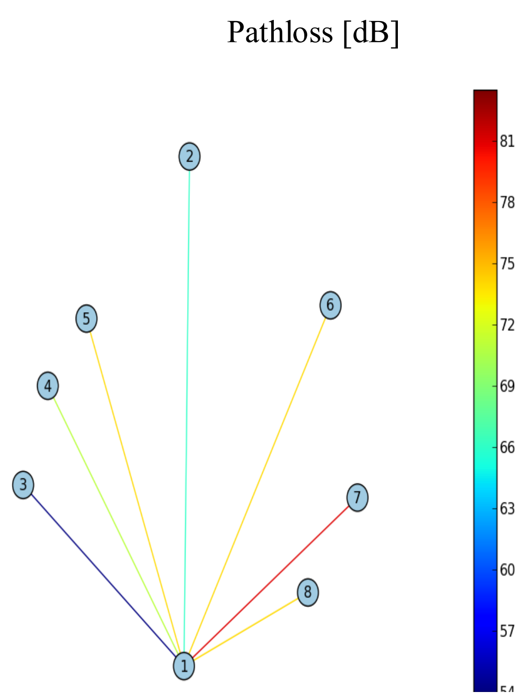

Figure 3. 15.c : Network graph (power level=23)

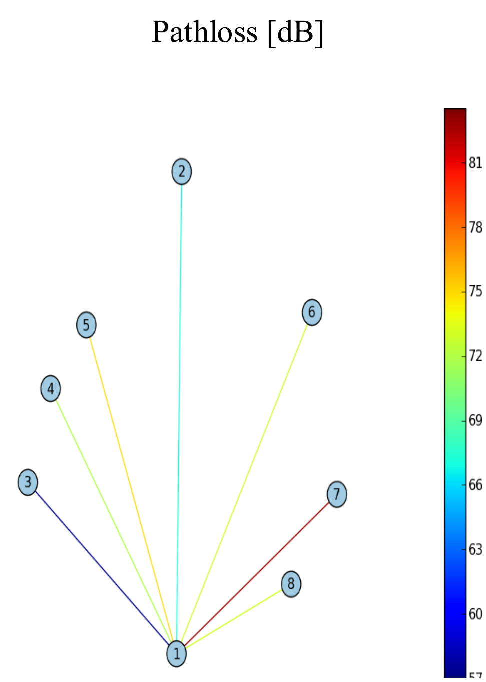

Figure 3. 16.d : Network graph(power level=31)

The figures shows that increasing the power level is an important factor to increase th connectivity between the motes mainly in the inner-building environments where the obstacles may affect the packets transmission which is the case in the figure 10.a where the link between the sender (mote(1)) and the receivers (motes (4),(7) and (8)) can not be established due the obstacles.

Increasing the power level permits also to ameliorate the link quality e.g the pathloss of link (1-2) with 6 dBm between the first and the last scenario.

To improve those results we implemented the RSSI measurement in a large scale network deploying 400 nodes across several floors/rooms in a building located in the Science and technology Park in São João da Madeira (SANJOTEC) **[8]** in Portugal. The measurements were done in one of the room of the building equipped with 29 motes.

The data collected permit to draw the network graph based on the pathloss values and using several power level in transmission see figures 3.11.a, 3.11.b and 3.11.c.

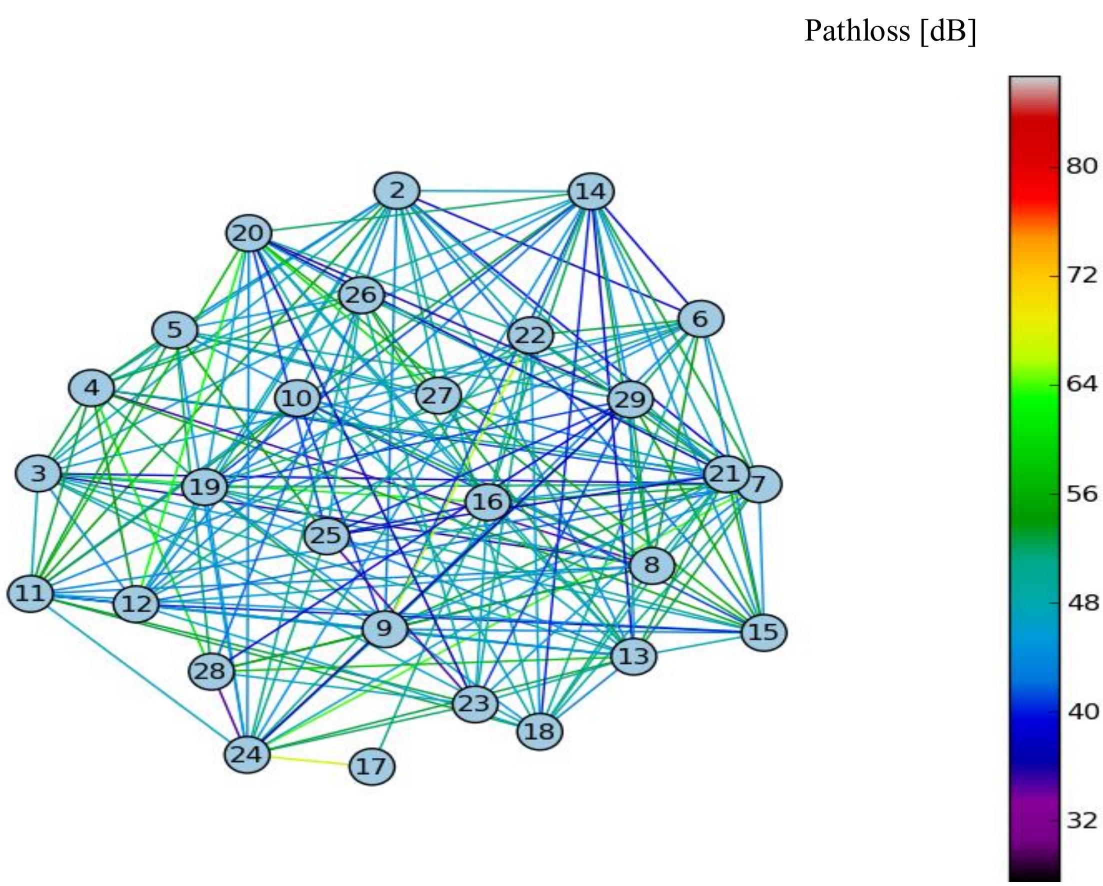

Figure 3. 17.a : Network graph (power_level = 3)

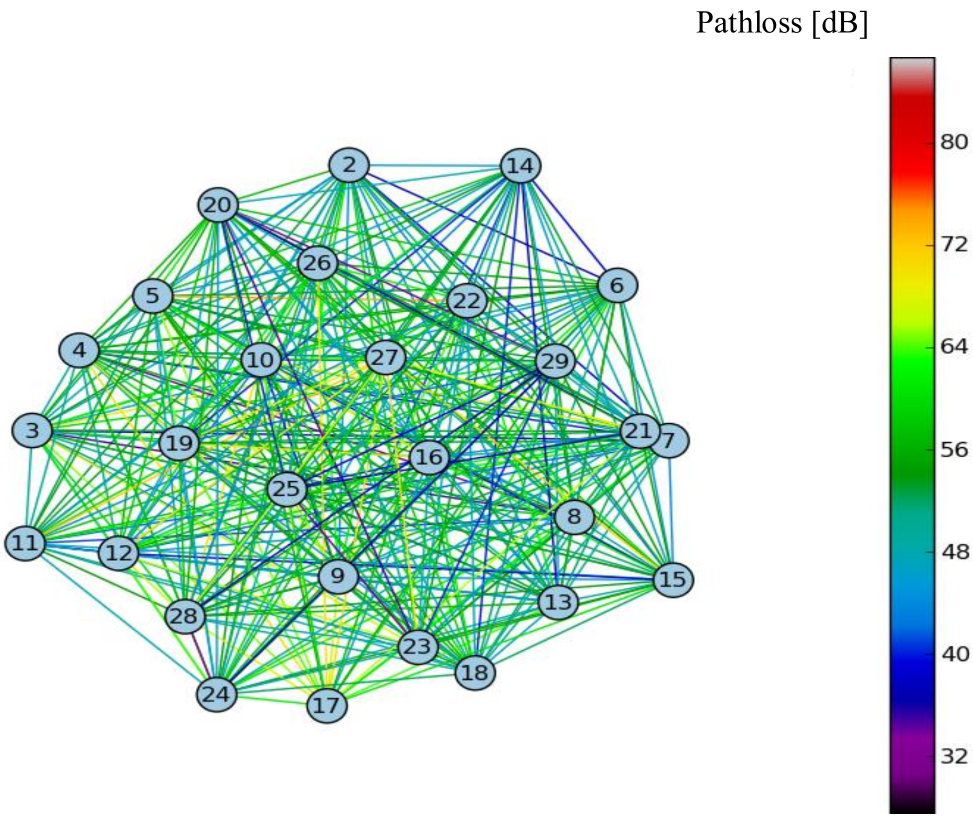

Figure 3. 18.b : Network graph (power_level = 17)

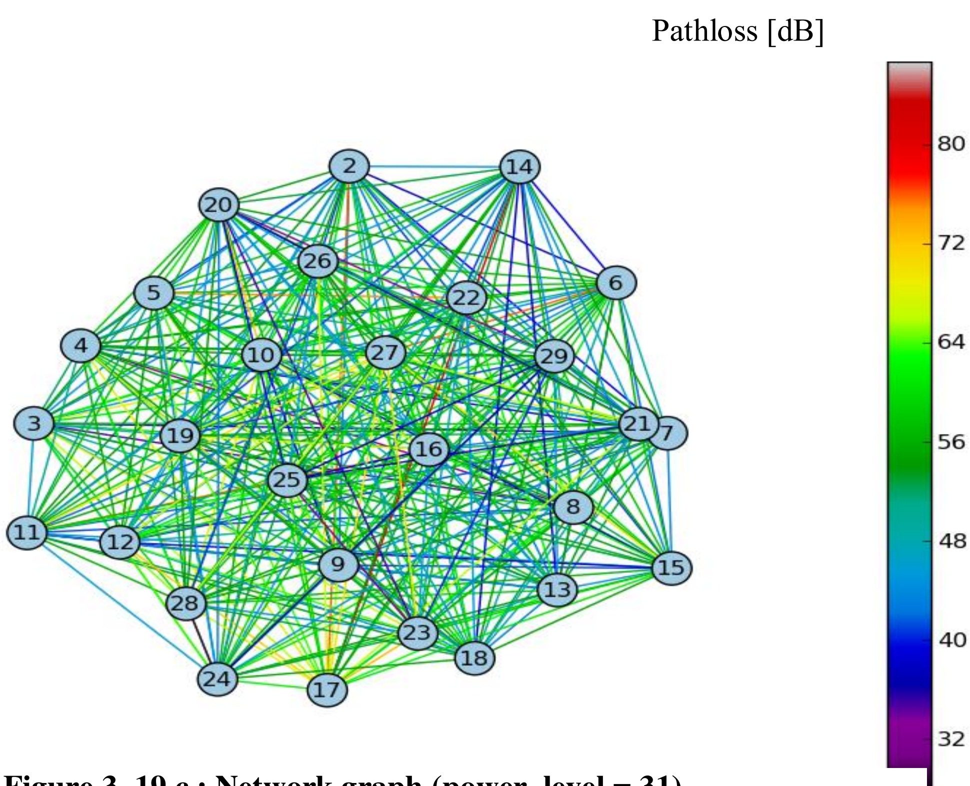

Figure 3. 19.c : Network graph (power_level = 31)

These figures show that increasing the power level has an important impact in the network density in term of direct link between the components of the network. Wireless sensor network are generally equipped with low-cost battery-powered nodes. Thus, we should minimize energy consumption without compromising the network connectivity and the ability to deliver data to a final destination.

Moreover, increasing the transmission power may increase the number of reachable node. Meanwhile, it impacts the network capacity by generating an important amount of interference affecting the transmission through the network.

Conclusion

The simulation done using Cooja and the experiment realized in CISTER permitted to study the result of the experiment implementation in different scenarios. We evaluated our approach of the sensor database that guarantees better use of the node capacity in term of memory.

Moreover we studied the different aspects affecting the data transmission and the network capacity. The analyzing tools that we developed permitted to explore the data collected to show how the channel and the transmitter power impact the link quality.

General Conclusion

The *wireless sensor network* has been considered, as a research and innovation area, an interesting issue in the networking and telecommunication field. The opportunities that offer this type of network permit a large deployment in different applications to collect data store it or transmitted to another device. This functioning is affected by the limited capacities of the nodes on term of computing, memory and mainly of memory energy. This limit is considered as the most critical issue in the WSN.

Therefore, a large number of researches focused on ameliorating the network capacity in energy management to guarantee a longer life time for the nodes and giving real interest to the links quality and the same time.

The aim of our work was to study how the radio communication in low-power wireless networks varies significantly with power and channel. This phenomenon shows that the previous topology control solutions based on transmission using a static power level or a static channel cannot guarantee the efficiency in real-world scenario.

In this context, we focused on, during our graduation project in the research lab CISTER, on studying the correlation between the link quality and transmission characteristics in term of power and frequency.

Therefore, we studied in the first the complexity of connectivity in wireless network, with emphasis on interference models, capacity and schedulability analysis

Moreover , we designed an experiment to better understand real-world interference scenarios in low-power wireless networks and implement the code in the Contiki OS to conduct them.

Finally, we debugged , tested ,evaluated the implementation in the Cooja Simulator, based on available radio models (UDG) and ported the code to large scale WSN testbeds.

The results of our work can be enlarged by designing MAC mechanism that offers a better efficiency in term of connectivity and reduce the interference effect by deploying an intelligent transmission power control and taking advantage of spatial reuse of the spectrum.

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