ABSTRACT

This thesis reasons on dynamic wireless sensor networks (WSN) analyzing different models and architectures. The main goal of all the work is the development of a tool designed to fulfill the needs of real on-field research, especially applied to indoor environment such as houses and hospitals. The idea was born from my last university thesis where alongside the original project of a remote controlled surgical room arose the need to monitor the hospital's patients and surgeons. In that occasion we were forced, for many reasons, to use a sort of batch system consisting of RFID tags and sensors with memory, whose data were downloaded after many hours or days, or simply sensors directly connected to computers. Instead a set of wireless sensors have allowed a real-time interaction with the remote controlled system.

My thesis first shows a background of the wireless sensor network theory, technologies and security issues and shows how the work was developed.

In the first period of time a developer starter kit was chosen from many available, evaluating different properties, including costs, open source or free IDE and the possibility of modify the base library supplied.

An initial project was developed using this kit, modifying the nodes to install the required sensors. Following the main requests of the team, the network was created balancing the energy consumption and the reliability. The developing work was supported by field tests on real research scenarios of increasing complexity. The initial test results on the original project, developed with the supplied library, revealed weaknesses in battery life, nodes connection stability and security thus changes were made accordingly. An heartbeat system was designed and implemented to create a fault tolerant system consisting in a couple of devices. Then the security issues were evaluated in consideration of the increasing number of attack's techniques designed for the WSNs. A cryptography key protection mechanism was implemented to protect the AES algorithm itself and the data, together with a software deletion mechanism, in front of an hardware read access, to avoid the steal of the initial pass-phrases of the program itself. Finally some consideration were made on the WSN performance and study results. In conclusion we can say that our wireless network has been used successfully, although it has shown limits on stability and data flow capacity. In most cases the WSN capacity of disappearing and to be unattended for long time were preferred then the data stream reliability because of the comfort quality perceived by study’s subjects (i.e. house's inhabitants or patients).

to my beloved Samuela
and all my family

Contents

1

Introduction

1.1 The statement

The wireless sensor networks are rapidly evolving in these years attracting interest in a number of application domains related with monitoring and control of phenomena, as they promise to accomplish tasks at low cost and with ease.

Researchers see WSNs as an “exciting emerging domain of deeply networked systems of low-power wireless motes with a tiny amount of CPU and memory, and large federated networks for high-resolution sensing of the environment” [WMC04].

In a WSN, the sensors have a variety of functions, and capabilities. The research’s field is now going forward under the push of recent technological advances and the pull of a plethora of potential applications.

Most of the actual sensor’s networks as the radars system, nation weather stations, country electrical power grid are all examples of sensor’s networks; however all these systems use specialized computers and communication protocols and consequently, are very expensive.

Much cheaper WSNs are now being developed for coming applications in security, health-care, and commerce. These systems are multidisciplinary and involves radio signals and networking, signal processing, systems architectures, database management, resource optimization, power management algorithms, and platform technology such as operating systems.

The networking principles and protocols of these systems are relatively young and are being developed in these years [KEW02].

The recent engineering advances coupled with many other factors as ubiquity of the Internet or the developments in IT, are opening the door to a new generation of low-cost sensors that are capable of achieving high-grade spatial and temporal resolution.

However there are many difficulties in application development that slow down the adoption of WSN technology.

In most cases the developers need to focus at hardware level to solve problems, requiring a very close knowledge of the operating system used beyond physical architecture.

According to [Mot06] the technical background needed is seldom found in high level domain experts and, as a second problem, the programmer usually loses the general view and application logic.

To simplify the developing without sacrifice the efficiency, a high-level abstraction is needed and several different solutions and approaches have been proposed.

In this thesis we study the development of a WSN, evaluating different approaches and techniques, building a complete system useful in real on-field researches.

1.2 Motivations

The main goal of this work is the development of a tool designed to fulfill the needs of real on-field research, especially applied to indoor environment such as houses and hospitals.

The idea of this study of such a WSN system arose during my master degree thesis [Gad06]. In that project study , started on 2003, we developed a prototype of a real-time control system of surgical theatres data flows.

While we did not find any particular problem gathering data from the surgical room programmable logic controller (PLC) and studying a possible evolution of such PLC, many problems were found trying to analyze the incoming data from patients and medical staff.

These human data are very valuable to estimate the infections (literature estimate the patient’s infection probability at more than 40%, with the 10% of the total with critical infection such as septicemia, (see [Sco09]) or hypothermia risks (even more dangerous than infections due to its direct implications to death) of the patient.

It is to underline that each critical infection, as an example, in the 2009 American implications infections cost report are declared to have a mean cost of over 13 thousands dollars [Sco09].

On the other hand the medical staff comfort, mainly the surgeons, is very important to reduce staff errors probability, especially in surgery requiring several hours.

In that study we were forced to use a sort of batch system consisting of RFID tags, sensors with their own memory and battery (iButton), whose data were downloaded after many hours or days, or simply sensors directly connected to computers. Instead a set of wireless sensors have allowed a real-time interaction with the remote controlled system.

The main reasons for such solution were the availability on the market of only ad-hoc systems with proprietary firmware that were designed to fit one specific problem and usually with an high cost. For instance the Bluetooth kit used in [FGM08], (kindly granted for a period from manufacturer at no cost) as a price of some thousands Euro and has all the typical problems of the Bluetooth devices: the modules cannot be used simultaneously due to their Bluetooth configuration and highly suffer the proximity of other Bluetooth devices (e.g. mobile phone often in the pocket of medical staff even when in a surgical room), moreover cannot cover areas greater than few meters (about 10m).

Moreover the Wireless Sensor Networks (WSNs) such as the ZigBee were, at time of the beginning of my master degree thesis, just at its first generation devices (a radio device without logic needing a separate MCU to perform most of the operations), and where considered more a new study field rather than a support to other projects.

If can be designed a WSN, capable of different kind of measurements, without interfering with the common patients and medical staff behaviors, it can be very useful to cover a wide range of applications allowing the monitoring, even for long periods, of the environments and their living peoples while they are performing everyday operations.

Finally we can say that literature lacks in these type of studies in many fields in which, instead, they can help to support or refute a theory.

1.3 Study context

My work was developed at CIAS (Centro Ricerche Inquinamento ambienti Alta Sterilità - pollution of high sterility environment research center) a interdepartmental research centre directed by professor S. Mazzacane and collaborating with different kind of scientists such as engineers, biologists, medical staff, IT staff, architects and sometimes physicists.

The centre cover many different areas starting with high sterility environments, such as cleanrooms, and indoor air quality (IAQ), including thermo-hygrometric and olfactory parameters, to reach issues related to mental or physical diseases. Sometimes two different areas converge into a unique research scenario such as in [Gad06] where the pollution and dust presence in a surgical room (a high sterility environment) controlled by our system prototype can be correlated to the patients’ infections.

The system design, of course, must be aware of this different application scenarios and needs.

1.4 Problems and challenges

As the project context suggest (see par. 1.3) the system must be designed to adapt to different situations, it needs to be easily divided into many networks if there are many concurrent studies or subjects to analyze. Thus, in our case, it is not suitable a special device that acts as a gateway from the WSN to a computer, but is much more useful that many devices can perform such a role. The second need of our system is the flexibility which means that we can easily:

- change the type of sensors, and this operation can be performed by any researcher. This problem involves both the hardware design, that can require modifications and the software development, for example building a modular sensors driver library
- change the way the nodes act in the network can be modified accordingly to their kind of activity (i.e. continuous measurements sampling or long idle periods). For this properties the application design must be as dynamic and event/environment driven as possible.
- place the nodes (or the sensors only) in hostile environments such as wet pipes or unattended locations. Usually we can achieve this goal protecting the node and choosing the sensors wisely.

The main features of the projected solution must be the non interference with the living people, this is of great relevance when trying to convince the potential subject's of study, as well as the possibility to monitor and interact with the system remotely, required not only by the cooperating research centre but also to achieve the non-interference task.

One of the main challenges, instead, come from the device energy consumption, since it can greatly affect the period of time the WSN can achieve its task without an external (and invasive) intervention.

Another challenge is the WSN coordinator bottleneck. In fact all network topologies where a central node exist where most of the traffic (in our case the data flow) needs to pass through, then this node will be a bottleneck. In WSNs this node is the gateway device (the WSN coordinator) that connects the WSN to other networks or to just a single computer.

Finally we must consider the node firmware, growing in size each time a new specifications set is released, taking the most part of the microcontroller memory (and sometimes computing) resources.

1.5 The approach

We start considering the WSN as part of a system to automatically gather data. The system required must be used in an inhabited environments with the less impact possible, avoiding any kind of discomfort to the living people.

We have studied the taxonomy of our researches and identified the minimum requirements to satisfy. This system must be flexible to adapt at many different contexts having the ability to change from a space time properties of type local/periodic (such as HVAC monitoring) to a much more intensive application global/event driven (such as environment condition or people action control-response).

Apart from the environment’s impact, the development time is also considered a crucial aspect, since most researches cannot wait months to start gathering data because of a software problem, most of the times, indeed, even a manual intervention is preferred to an automatic system non really reliable and inefficient.

We have started from the WSN state of the art [BPC07] to evaluate the best solution to fit our WSN system, we have chosen the ZigBee WSN as a large recognized emerging standard with several manufacturer proposals and we have used one of this proposal to develop our system.

We have finally used our studies as a test-bed field to prove how really efficient and flexible is the WSN system. To achieve the task of sensor interchangeability we have designed a modular library that can be reduced (with only a sensors driver selection) for memory requirements. In this way the nodes can be configured by a command sent via the WSN coordinator without the need to change the node firmware itself but just needing a warm reset (usually the reset request is also sent via the coordinator device).

We have partially redesigned the upper layer (the Network layer) to solve some communication problems such as isolated nodes, timer malfunctions and to dynamically change the node role inside the network. To add more reliability to the application we have also implemented an heartbeat system, that is not a new idea, but is adapted to a wireless context using the beacons of the first device as the beat signals and, moreover, saving the battery energy of the second node.

On the test results basis we have, also, improved the WSN reliability and security covering the weakness found, such has the possibility to read the AES key from the node memory or the flaw against DOS attack exploiting the AES-CTR procedure.

Moreover a Network Intrusion Detection System (NIDS) was modified to use a special WSN node (a network sniffer) and a packet capture library to gather and monitor ZigBee network traffic.

Finally to improve the WSN performance we have implemented a Huffman compression algorithm (only the compression with a static table on the node) due to its simplicity and compression speed, this partially solve the bottleneck problem when we have a single sensor (e.g. an tri-axial accelerometer) producing an high data flow (90 values/sec or more), but the WSN can also be split into many networks since each node can act as the coordinator.

Part of the system design effort has been directed to the applications projected to gather the data from the WSN, send the data to the database server. For performance and memory reasons the application is multithreaded (and can be executed without problems on a Pentium III PC).

Furthermore a web interface was created to allow the scientists' remote access. This actual system shows the data with a delay of few seconds (typically less than 2 seconds) thus, for the kind of requirements we have, it can be considered a real-time system.

1.6 Organization of the thesis

Apart from this introduction the following chapter propose an overview of the Wireless Sensor Networks. In the third chapter are shown the WSN classification, standards, and protocol layers.

Next are proposed some WSN implementation aspects used while developing the application such as network formation, routing algorithms and security issues. It's also includes some of the ZigBee higher layers because of their been both accessed and modified during the application developing.

The fifth chapter aims to describe the author work done starting from the choice of the devices and their hardware modifications, to the completion of WSN application.

The subsequent chapter is dedicated to the results achieved by our WSN system, thus are described the benchmark, throughput and lifetime results obtained and the on field test applications with their relative gateway applications.

Finally in the last chapter were presented the author’s conclusions and perspectives for the future works.

2

WSN Applications

2.1 Application domains

We can briefly see the main application domains for the WSN as described in [Cal06]. The environment can be the physical world, a biological system, or an information technology (IT) framework. And new doors are opening everyday as a result of the technology improvements.

We must not forget that a stated goal is to develop complete MEMSs–based sensor (micro-electro-mechanical systems) at a volume of 1 mm^3 [WMC04].

2.1.1 Industrial control and monitoring

A industrial facility has a relatively small control room, surrounded by a large plant. The control room has usually several indicators and displays that describe the state of the plant (valves, quantity, temperature and pressure of stored materials, equipment’s condition, and others) and input devices that control actuators in the plant (heaters, valves, etc.) that affect the state of the plant itself.

The sensors, their displays, the input devices and the actuators are often relatively inexpensive compared with the cost of the armored cable that must be used to communicate in a wired installation.. The information shown usually changes slowly so the data bandwidth required is relatively small although a high reliability level is required.

The costs can be significantly reduced if an inexpensive wireless communication is used instead and a multiple routing network can be used to maintain the reliability level.

An example of wireless application in an industrial environment [Cal06] is the control of commercial lighting. A wireless system can be programmed to control the lights, grouping them with ease to turn on and off simultaneously, cutting down the expense of all wired switch and can be much more flexible when a change is needed.

The monitoring and control of moving machinery, where wired sensors and actuators are often unusable, is another area suitable for wireless networks.

Because the wireless networks may implement distributed routing algorithms and can be self-healing they can proof to be resilient to an explosion or other serious damage to the industrial plant, providing officials with critical plant status information under difficult conditions.

To accomplish to such a job it is important that the wireless system be fully operating for the entire interval between maintenance periods.

This implies, among others the use of a wireless sensor network with very low energy requirements.

The sensor node often must be small, inexpensive and easy to substitute. Wireless sensor networks may be of particular use in the prediction of component failure for aircraft, where these attributes may be used to particular advantage [Fri01].

Another application in this area for wireless sensor networks is the heating, ventilating, and air conditioning (HVAC) of buildings.

This is one of the application also of the WSN developed during my thesis period.

HVAC systems are typically controlled by a small number of thermostats and humidistat strategically located. Once more the wired connections limit the possibility and the number of these thermostats and humidistat

To improve the granularity response of a HVAC system wireless handlers and dampers can be used coupled with wireless thermostats and humidistat sensors that may be placed around each room to provide detailed information about the control system. So the HVAC system can fit the need of the working team, for example reducing the volume dampers for an empty project-room and opening dampers for the meeting-room while in use. A wired system usually lacks to accomplish such a task.

2.1.2 Home automation and consumer electronics

There are many possible applications for wireless sensor networks at home. [Cal02]. Many of the industrial applications, someone described in the previous paragraph, may be used in a home, for example a HVAC system exist, and equipped with wireless thermostats, dampers and the right sensors can keep the rooms of the house comfortable in a way more efficient than a home equipped with a single and wired thermostat.

However, a lot of other opportunities are available, like the “universal” remote control, typically a PDA (personal digital assistant) device that can control not only the TV, CD player, but the lights, any kind of curtains, locks that are also equipped with a wireless sensor network connection.

With this remote control, one may control the house from the comfort of one's armchair.

One of the most interesting application, however, comes from the combination of multiple services, such as closing the curtains automatically when the television is turned on, or automatically muting the entertainment system when a call is received on the telephone.

Another application in the home is a sensor-based information appliances that transparently interact and work together as well as with the home occupant [Pet00]. These networks are an extension of the information appliances proposed by Norman [Nit06].

Toys represent a large market for wireless sensor networks, they can be enhanced or enabled by wireless sensor networks in several ways, limited only by one's imagination.

A particularly interesting field is PC-enhanced toys, which use the computing power of a nearby computer to add functionality to the toy itself, for example, speech recognition and synthesis, without placing the expensive yet limited speech recognition and synthesis circuits in the toy but using the computing power of the computer. The overall cost of the toy will be reduced improving its capabilities and performance.

It is even possible to give the toy complex behavior not practical with other technologies (see http://toys.media.mit.edu/).

Another home application is similar to the Remote Keyless Entry (RKE) feature found on many cars. With a WSN, wireless locks, door and window sensors, and wireless light controls, the home owner may have a remote control similar to a car-key with a button. When the button is pressed, the device locks all the doors and windows in the home, and additionally can turns off the programmed indoor lights, turns on outdoor security lights, and sets the home's HVAC system to nighttime mode.

The user receives an ok sound once this is all done successfully or an error code if something goes wrong and in this case he can read on the display where is the source of the problem. Also a full home security system can be implemented as well to detect a broken window or other troubles.

Outside of the home, the wireless sensor networks are suitable for many of activities consumer-related, like tourism and shopping [ACK94].

In these contexts WSNs can provide, furthermore, specific information about the consumer’s behaviors .

2.1.3 Security and military sensing

The security system described in the previous paragraph for the home environment can be use in industrial security applications.

Similar systems have existed for several years [Swa96] employing proprietary communication protocols.

They can support multiple sensors relevant to security, including magnetic door opening, infrared, broken glass sensors, smoke and sensors for direct human intervention.

One of the benefits of using wireless sensor networks is that they can be used to replace guards and sentries, not only in military field, around defensive perimeters.

In addition wireless sensor networks can be used to locate and identify targets for potential attack or to support the attack by locating friendly or enemy troops and vehicles.

Wireless sensor networks can be camouflaged to look like rocks, trees, or gravel. These networks, are difficult to destroy in battle, thanks to their distributed control and routing algorithms [Hew01].

The use of spread spectrum techniques, combined with the burst transmission format, common to many wireless sensor networks (to optimize battery life), can give them a low probability of detection by electronic means.

2.1.4 Asset tracking and supply chain management

A lot of application of wireless sensor networks is expected to be concerning resource tracking and supply chain management.

One example is the tracking of containers in a port. Such port facilities may have thousands of containers or even more, some of which are empty,

while others are to be shipped in different destinations and they are stacked, on land and on ships.

The efficiency of organization is an important factor in the shipper's productivity so that they can be moved the fewest number of times and with the fewest errors. [Cal06]

An error in the location record of any container can be very expensive and the lost container can usually only be found by an exhaustive search.

Wireless sensor networks can be used to improve such required efficiency; by placing sensors on each container, its location can always be determined.

Similar problems can be found in railways transport system where railroad cars of different types must be organized, and in the industries of non-durable goods.

The use of wireless sensor networks for the tracking of nuclear materials has already been demonstrated in the Authenticated Tracking and Monitoring System (ATMS) [Sch98], [Sch00].

The ATMS profit from wireless sensors (state of the door, infrared, smoke, radiation, and temperature sensors) within a shipping container to monitor the state of its contents. Notification of events are transmitted within the shipping container via a wireless system to a mobile processing unit connected to a GPS receiver and an International Maritime Satellite (INMARSAT) transceiver. Through the INMARSAT system, the location is well known and so is the status of each shipment which may be monitored anywhere in the world.

2.1.5 Intelligent agriculture and environmental sensing

An example of the use of wireless sensor networks in agriculture is the rainfall measurement. Large farms and ranches may cover several square kilometers, and they may receive rain only occasionally and only on some portions of the farm. Thus it is important to know which fields have received rain, so that irrigation, usually expensive, can be omitted and which fields have not and must be irrigated.

Such an application is ideal for wireless sensor networks. The amount of data sent over the network is usually very low (if is of type "yes or no rain" is just of one bit), and the message latency can be on the order of several minutes. However costs must be low and energy consumption must be low enough for the entire network to last an entire season.

The wireless sensor network is capable of much more than just rain soil measurements because the network can be fitted with a large variety of chemical and biological sensors.

This type of application is very important in vineyards, where environmental changes may have vexing effects on the value of the final product.

The location determination features of wireless sensor networks may be used in advanced control systems to enable more automation of farming equipment or in the determination of animals' position.

Wireless sensor networks may also be used for low-power sensing of environmental contaminants such as mercury [Bri98].

MEMS sensors may be integrated with a wireless transceiver in a standard CMOS process, providing a very low-cost solution to the monitoring of chemical and biological agents.

2.1.6 Health monitoring

“Health monitoring” is usually defined as “monitoring of non-life-critical health information”, to differentiate it from medical telemetry, and in this field wireless sensor networks is expected to grow quickly, although WSN can applied to some telemetry application as well.

We can classify health monitoring applications into two general classes available for wireless sensor networks. The first class is athletic performance monitoring, for example, tracking one's pulse and respiration rate via wearable sensors and sending the information to a personal computer for data analysis [Ber01]. The second class is at-home health monitoring like personal weight management [Par00].

The patient's data can be wirelessly sent to a personal computer and then be used, analyzed or just saved. Another example is the remote monitoring of patients with chronic disorders like diabetics [Lub02].

The use of wireless sensor networks in health monitoring is expected to increase rapidly due to the development of biological sensors compatible with conventional CMOS integrated circuit processes [YLH02].

The sensors, which can detect nucleic acids, enzymes, and other biologically materials, can be very small, enabling their applications in pharmaceuticals and medical care.

A developing field market is that of implanted medical devices. In the USA, the Federal Communications Commission (FCC) established rules governing the Medical Implant Communications Service, "for transmitting data in support of diagnostic or therapeutic functions associated with implanted medical devices." (see http://wireless.fcc.gov).

A developing field related not only to health monitoring is that of disaster relief. For example, the wireless sensors of the HVAC system in a collapsed building (earthquake event or gas explosion) can provide victim location information to rescue workers if acoustic sensors, activated automatically by accelerometers or manually by emergency personnel, are included.

Wireless disaster relief systems like avalanche rescue beacons, which continuously transmit signals, are already on the market, so that rescuers can use to locate the wearer while is in an emergency situation, are used by skiers and other mountaineers in avalanche-prone areas.

The actual systems have their limitations, first of all they provide only location information, and give no information about the health of the wearer. Thus in a large avalanche, when several beacons can be detected by emergency personnel, There is no way to decide who should be assisted first.

It was recently proposed that these systems be enhanced by the addition of health sensors, including oximeters and thermometers, so that would-be rescuers would be able to identify those still alive under the snow [Mic02].

2.2 Network performance objective

To meet the requirements of the applications just described, a wireless sensor network design must achieve several objectives. The need for these features leads to a combination of technical issues not found in other wireless networks.

2.2.1 Low power consumption

WSN applications usually require network components with a power consumption that is lower than currently required by implementations of existing wireless networks such as Bluetooth.

For example, devices for certain types of smart tags, badges, or medical sensors powered from small coin cell batteries, should last for several months or even years.

The monitoring and control applications of industrial equipment require exceptionally long battery life so that the maintenance schedules of the monitored equipment are not compromised. Other applications may require a very large number of devices that make frequent battery replacement impractical.

Moreover there are applications that cannot employ a battery at all; network nodes in these applications must get their energy from the environment [Sta99]. An example may be the wireless car tire pressure sensor, for which it is desirable to obtain energy from the mechanical or, as alternative, thermal energy present in the tire instead of a battery that may need to be replaced before the tire does [Cal06].

In addition to low power consumption a system with limited power sourcing often has limited peak power sourcing capabilities as well and this is an important factor to consider in system design.

2.2.2 Low cost

Cost plays an important role in applications adding wireless connectivity to inexpensive systems, and for applications with a large number of nodes.

Most applications require wireless links of low complexity and low cost relative to the total product cost.

To meet this objective, the network design and communication protocol must avoid the need for expensive components, such as discrete filters, by employing relaxed analog tolerances wherever possible, and minimizing memory and computing requirements [Cal06].

However one of the largest costs of many networks is administration and maintenance. Thus to be a true low-cost system, the network should achieve ad-hoc, self-configuration and self-maintenance capabilities.

An “Ad hoc” network is a network without a predetermined logical topology or physical distribution.

“Self-configuration” is the ability of network nodes to detect the presence of other nodes and to organize into a structured network without human intervention.

“Self-maintenance” is the ability of the network to detect, and recover from, faults in either network nodes or communication links without human intervention.

2.2.3 Security

The security of wireless sensor networks involve two factors of equal importance: how secure the network is and how secure the network is perceived to be by users.

The perception of security is very important because users have a natural concern when their data is transmitted over the air.

Moreover, an application employing wireless sensor networks often replaces a wired version in which users could physically see the wires or cables carrying their information, and know that no one else was intercepting their information or injecting false information with reasonable certainty.

The wireless systems must work to reach that feeling to achieve the wide market needed to lower costs.

However security is more than just message encryption. In fact encryption is not an important security goal of wireless sensor networks.

Usually the most important security goals are to ensure that any message received has not been modified in any way and is from the sender who claims to be.

In fact if one has a wireless light switch in a home, there is little to be gained by encrypting the commands “turn on” and “turn off”.

Any potential eavesdropper know that only two possible commands are likely, but he or she may also be able to see the light shining out the home window from his or her position.

Therefore having secret commands in this application is of little importance.

What is really important is that the malicious eavesdropper in the street can not be able to inject false or modified messages into the wireless sensor network, with the possibility of causing the light to turn on and off as he likes.

This requires message authentication and integrity checking, which is performed by appending to a message a sender dependent Message Integrity

Code (MIC sometimes known as MAC Message Authentication Code) to the transmitted message.

The desired recipient and sender share a key, which is used by the sender to generate the MIC as well as by the recipient to confirm the integrity of the message and the identity of the sender.

To avoid the "replay attacks" in which an eavesdropper records a message and retransmits it later, a message counter or timer must be included in the calculation of the MIC. In this way two authentic messages containing the same data will not be identical.

Regarding security the wireless sensor network engineer faces three main difficulties: the length of the MIC must be balanced according to the typical length of transmitted data, and the desire for short transmitted messages. Although a 16-byte (128-bit) MIC is often cited as necessary for the most secure systems, it becomes cumbersome when single-bit data is being passed (e.g., on, off).

The designer must balance the security needs of the users with the low-power requirements of the network. Note that this may involve not only choices of MIC length but also combinations of message authentication, integrity checking and encryption and must be automatically performed, as part of a self-organizing network.

To minimize the cost of the network devices, the security features must be capable of implementation without an expensive hardware, with a minimum addition of logic gates and memory (RAM and ROM).

Since the computational power available in most network devices is very limited, the combination of low gate count, small memory requirements, and low executed instruction count limits the security algorithm's types available.

The last but perhaps the most difficult problem is key distribution. Many methods are available, including several types of public key cryptography, employing dedicated key loading devices and various types of direct user intervention.

All have their advantages and disadvantages when used in a given application so the wireless sensor network designer must select the appropriate one for the application developed.

WSN have additional requirements including, fault tolerance, scalability to very large networks, and the need to operate in hostile environments [Aky02].

Although the design of a network that meeting these requirements may seem difficult, usually they don't need to be achieved all simultaneously in the same system, for example the strict power and cost requirements come with more relaxed requirements in other areas.

2.2.4 Network type

Although a star network with a single master and one or more slave devices may satisfy many applications, the transmit power of the network devices is limited by government rules and battery life concerns, network types that support multi-hop routing must be employed when additional range is needed.

The additional memory and computing cost for routing tables and algorithms, in addition to network maintenance and overhead, must be supported without excessive cost or power energy consumption.

It is to be emphasized that many applications are of relatively large order (hundreds of nodes) and device density may also be high (for example in market price tag applications).

2.2.5 Worldwide availability

Several proposed applications of WSN, such as wireless luggage tags or shipping container location systems, require that the network be capable of fully operate worldwide.

Additionally, to maximize efficiency of products, production, marketing, sales, and distribution and to avoid the establishment of proprietary or regional variants, it is desirable to produce devices capable of worldwide operation.

Although this capability can be implemented by employing GPS or GLONASS receivers in each network node, the cost of adding a second receiver, plus the additional performance required to meet the varying worldwide requirements, makes this approach economically impractical.

It is, instead, preferable to employ a single band worldwide, one that has minimal variation in government regulatory requirements to maximize the total available market for wireless sensor networks.

2.2.6 Data throughput

Wireless sensor networks have limited data throughput requirements compared with Bluetooth (IEEE 802.15.1) and other WPANs and WLANs.

The maximum desired data rate, according to [Cal06], averaged over a long period, may be set to be 512 b/s, although this is rather arbitrary.

The typical data rate is expected to be below this; even 1 b/s or lower in some applications. It needs to be underlined that those values represent the data throughput, not the data rate transmitted over the channel, which may be significantly higher.

This low amount of data throughput implies that, with any practical protocol overhead, the communication efficiency of the network will be very low (especially when compared against TCP/IP packets that may be 1500 bytes long).

Regardless what design is chosen, the efficiency will be very low, and the situation, therefore, may be viewed in positive: the protocol designer has the possibility to design free of the consideration of communications efficiency, usually a critical parameter in protocol design.

2.2.7 Message latency

Wireless sensor networks have soft Quality of Service (QoS) requirements, because, in general, they do not support synchronous communication, and have data throughput limitations that disallow the transmission of applications like real-time video and voice. The message latency requirement for wireless sensor networks is, therefore, very relaxed in comparison to that of other networks. In fact, while the LAN has a typical latency of 1-10ms and the WLAN has a latency period of 5-20ms, the WSN start from a latency value of 150 ms to many seconds (e.g. for sleeping nodes).

2.2.8 Mobility

Wireless sensor network applications, in general, do not require the nodes to be moved from their starting places. And usually WSNs suffer less control traffic overhead and may employ simpler routing methods than mobile ad hoc networks, because the network is released from the burden of look up for open communication routes, (e.g., MANET)

2.2.9 Size

To achieve the main goals of low-cost, mass production and low energy consumption it is fundamental that a node is as small as possible in size. It will be also much easier to place the nodes, even in hostile environment, while design the wireless sensor network.

With the progress of silicon processes, transceiver systems decrease in size. Forty years ago, for example, a simple transceiver was a shoebox sized device of about 10 kg. Today the radio transceiver has become a single piece of silicon, less then a coin in size (fig. 2.1), with few passive components.

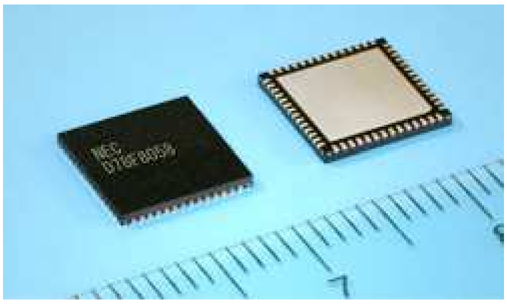


Figure 2.1 - NEC Electronics 16-bit Microcontrollers with Embedded Radio Transceiver

Most of the microcontrollers today have native ability to interface with sensors (built-in digital I/O and A/D converters). The 8-bit or 16-bit microcontroller may already include 64 or even 256 kilobytes of flash memory, RAM, and various hardware timers, along with the ability to interface directly to the radio transceiver. The MCU requires few external components to be fully functional.

Therefore, the silicon system size of a WSN node is usually smaller than the batteries they use. This compact form factor lends itself well to innovative uses of radio technology in sensor applications. Integration is the key issue, and even higher levels of integration will be achieved in the future 802.15.4 platform.

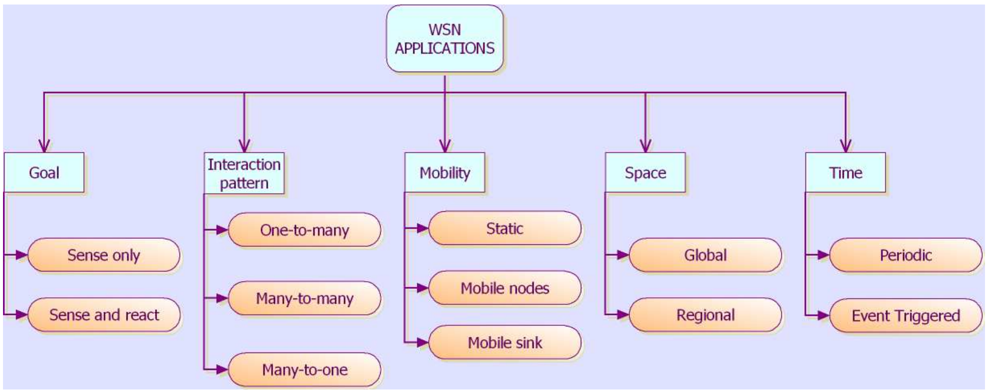


Figura 2.1 - A WSN taxonomy

2.3 WSN application taxonomy

WSNs are mission-driven systems that provide a task efficiently. Since WSN are service providers they can be modeled at different levels of abstraction. To better understand the WSNs properties and characteristics there is a need for a classification and definition of WSN applications.

To build such unambiguous classification scheme we start considering the main properties of the systems.. This scheme is analogous to an object-oriented classification, where an object is described by its attributes and is classified on the basis of its capabilities,. The properties of the wireless applications are grouped into five categories: goal, interaction pattern, mobility, space and time. Each of these are further classified to provide sufficient details that are required for a typical WSN application.

The classification scheme is depicted in figure 2.1 while for a classification of the WSN devices refers to[ChE06]

3

WSN classification and standards

3.1 A definition of WSN

A sensor network is an infrastructure include measuring, computing, and communication elements that gives someone the ability to observe and react to events in a specified environment. [SMZ07].
Thus a wireless sensor network (WSN) can be defined ([VDM06], [Cho06]) as a network of devices, possibly low-sized, denoted as nodes that can measure some physical environmental phenomena and communicate the information gathered from the monitored field through wireless links, possibly via multiple hops relaying, to one or more sinks (named controller or monitor) that can use it locally or is connected to other networks through a gateway. The sink can be a common node or a specialized device with an increased power computing and memory capabilities.
The nodes can be stationary or moving, aware of their location or not, homogeneous or not.

Network sensor systems are seen as an important technology that will experience major deployment in the next few years for a multitude of applications discussed in the next paragraph.
There are four basic components in a sensor network [SMZ07]:

- a set of distributed sensors;
- an interconnecting network (in our case wireless-based);
- a central point for coordination and of information processing;
- a set of computing resources at the central point (or beyond) to handle the data flow, correlation, event trending, status querying, and knowledge discovery.

In this system the nodes, with sensing and computation capability, are considered part of the sensor network as some of the computing may be done in the network itself.

The algorithmic methods for data management, because of the large quantity of data that can potentially be collected, play an important role in WSN.

The computation and communication infrastructure associated with sensor networks is often specific to this environment and rooted in the device and application-based nature of these networks.

For example, unlike most other settings, in-network processing is desirable in sensor networks; furthermore, node power (and/or battery life) is a key design consideration.

There are a number of different types of networks whose classifications are based primarily on the distances they may reach [Lew04].You see in Table 3.1 how they relate to the wired world and to each other.

Table 3.1	Different Types of Networks	
Network Type	Wired	Wireless
Local Area Network (LAN)	IEEE 802.3 (Ethernet)	IEEE 802.11X
Personal Area Network (PAN)	IEEE 1394 USB	IEEE 802.15.1 IEEE 802.15.3 IEEE 802.15.4
Metropolitan Area Network(MAN)	Broadband (DSL, cable)	IEEE 802.16

Table 3.1 – type of network

The WSN discussed in this thesis are usually classified as WPAN networks.

The IEEE (Institute of Electrical and Electronics Engineers) provides standards for wired and wireless networking. The numbers are assigned by the IEEE and become well known to industry users. The 802 series dictates how each format must work. You can obtain lots of interesting information about these standards and their use from various Web sites (like www.dailywireless.org).

The IEEE formed the WPAN Study Group in 1998. The study group’s main goal was to investigate the need for a wireless network standard for devices within a personal operating space (POS). In the same year the Bluetooth Special Interest Group (SIG) was formed. In 1999 the WPAN study group became IEEE 802.15 (WPAN Working Group). The 802.15 WPAN

(Wireless Personal Area Network) is an effort to develop standards for short distance wireless networks

These WPANs includes wireless networking of portable and mobile computing devices, such as PCs, Personal Digital Assistants (PDAs), peripherals, cell phones, and pagers, letting these devices communicate with each other.

Since the formation of 802.15 four sub-projects have started, including Bluetooth (Bluetooth 1.0 Specification in released in July of 1999) and the co-existence of 802.11 and 802.15 networks, and 802.15.4 as well as a standard for high bit rate (20 Mbps or higher) WPANs.

In general WSNs techniques (contention-oriented, channel sharing and transmission) are now incorporated in the IEEE 802 family of standards, indeed, these techniques were originally developed in the late 1960s and 1970s expressly for wireless environments and for large sets of dispersed nodes with limited channel-management computing capabilities. [SMZ07]

3.2 WSN classifications

A WSN as defined in paragraph 3.1 is a distributed systems (see [Cal06]) composed of several embedded devices, each equipped with a processing unit, a wireless communication interface, and many sensors/actuators.

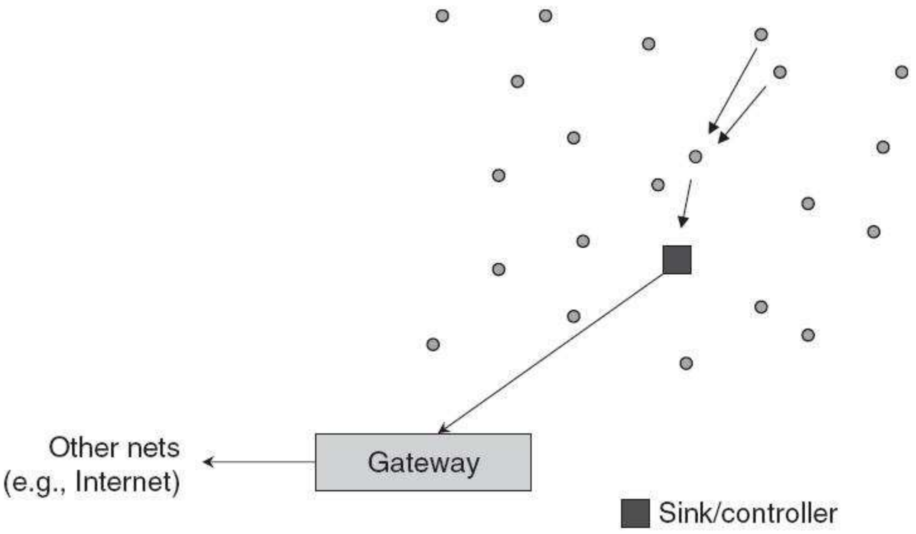


Figure 3.1 - single-sink WSN

Usually in these scenarios tiny battery powered devices are used, so that deployment results easy and increase the global flexibility [Aky02], providing low-cost, fine-grained interactions with the environment.

The result of the definition of WSN in paragraph 3.1 lead to a traditional single-sink WSN (Figure 3.1).

Most of the scientific papers in the literature deal with such a definition but this single-sink scenario suffers from an obvious bottleneck ([VDM06]) which implies a lack of scalability: increasing the number of nodes also the amount of data gathered by the sink also increases and once its capacity is reached the network size can not be augmented.

Furthermore, for reasons related to the MAC (medium access control) and routing aspects discussed later, the global network performance cannot be independent from the total network size.

3.2.1 Single-sink single-hop WSN

We can give an evaluation of the capacity of a single-sink single-hop WSN, as in [VDM06], defined in terms of maximum number of nodes that a sink can accept.

We consider a WSN where nodes are requested to send their samples (composed of D bytes each) taken from the monitored space every T_R seconds. Initially we may assume that all nodes send their data directly to the sink (a star topology). N Denote the number of nodes, R_b the channel bit rate. Taking account of the overhead introduced by protocol stack layers, we define a factor, $\alpha_A \leq 1$ thus if S_A is the maximum data throughput measured at the application layer, then will be $S_A = R_b \cdot \alpha_A$.

All protocol layers contribute to lower α_A and reducing it will lower the throughput even if the channel bit rate is unchanged. In modern communication systems α_A typically is a value between 0,5 and 0,1 [VDM06].

Under such assumptions, the application throughput will be approximately equal to $N \cdot D \cdot 8 / T_R$. Thus, we arrive at the following inequality:

$$N \cdot D \cdot 8 / T_R \leq R_b \cdot \alpha_A$$

Therefore we can assert

$$\textbf{(3.1)} \quad N \leq R_b \cdot \alpha_A \cdot T_R / (8D)$$

This equation rappresents an approximate estimation of the number of nodes that can be part of a single-sink single-hop WSN. To give a numerical example, assume R b = 250 Kbit/s,

T_R = 1s, α_A =0,1, D = 3; then the maximum number of nodes is approximately 1000. On the other hand, if T_R = 50 ms, then N can not exceed 50.

As seen the requirements of the application play a relevant role when defining the capacity of a single-sink WSN and also that the protocol overhead can play a significant role, through α_A.

In the case discussed above, the nodes are all within range of the sink. If the transmission range of links between sink and nodes is R, then the density of nodes for a bidimensional space is (no smaller than)

$$N / \pi R^2 .$$

3.2.2 Single-sink multi-hop WSN

Now we will assume that the N nodes are distributed according to a smaller density, thus some of them must reach the sink through multiple hops. If a node can send its sample to the sink through h hops, then the delivery of the data sample requires h transmissions.

Let us denote by h_m the average number of hops per data sample taken from the fi eld; if no smart reuse of radio resources is introduced, then we have for a single-sink multi-hop WSN [VDM06]

$$\textbf{(3.2)} \quad N \leq R_b \cdot \alpha_A \cdot T_R /(8Dh_m)$$

Therefore, the capacity of the network is reduced by a factor of h_m .

3.2.3 Multi-sink multi-hop WSN

A more general scenario includes multiple sinks in the network (see Figure 3.2). Maintaining the same node density, a larger number of sinks will decrease the probability of isolated group of nodes that cannot deliver their data due to an unfortunate signal propagation.

Moreover a multiple-sink WSN can be scalable: in fact, the same performance can be achieved even by increasing the number of nodes, while this is not true for a single-sink network.

Still a multi-sink WSN does not represent a trivial extension of a single-sink case. There are mainly two cases:

All sinks are connected, wired or wireless, through a separate network,
The sinks are disconnected

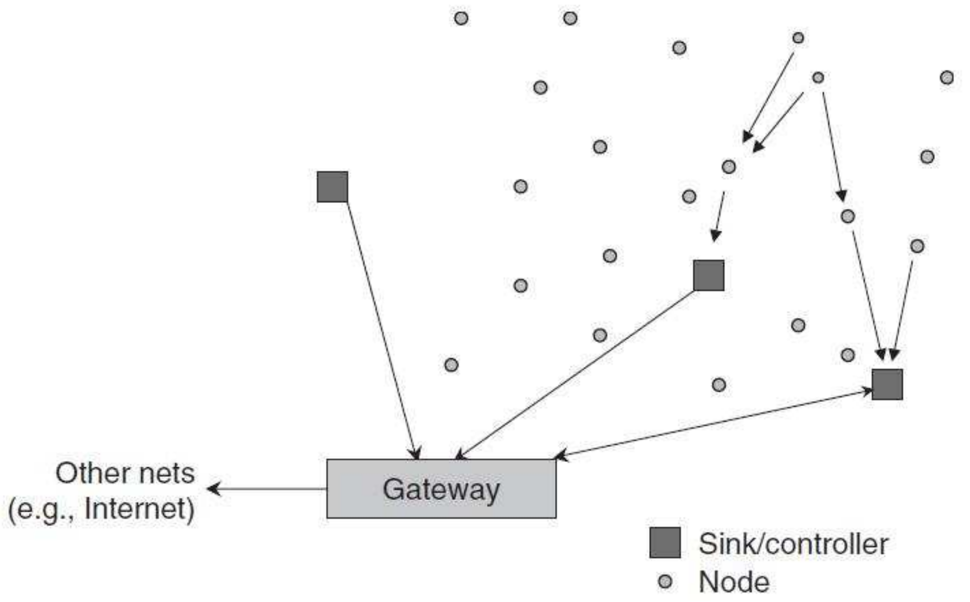


Figure 3.2 -Multi Sink WSN

In the first case, a node needs to forward the data collected to any of the sinks.

From the protocol viewpoint, this means that a selection can be done based on a suitable criterion (e.g., minimum delay, maximum throughput, minimum number of hops).

in this case the presence of multiple sinks ensures better performance then the single-sink network with an equal the number of nodes in the same area, but the communication protocols will be more complex.

In the second case, when the sinks are not connected, the presence of multiple sinks just make a partition of the monitored field into smaller areas; however from the communication protocols viewpoint there are no significant changes, apart from simple sink discovery mechanisms.

Because of the better potential performance, the first case is clearly the most interesting due to the sinks connected through any type of mesh network is clearly the most interesting case.

We can do an approximate evaluation of the capacity of a multi-sink WSN, assuming that each sink (denoting as N_S their number in the network) can serve N nodes with N limited by expressions (3.1) and (3.2).

We can assert:

$$\textbf{(3.3)} \quad N \leq N_s R_b \cdot \alpha_A \cdot T_R /(8Dh_m)$$

assuming that group of nodes attached to a given sink do not interfere with those attached to other sinks. To give a numerical example we will use the same value as for the single sink case: R_b = 250 Kbit/s, T R = 50 ms, α_A = 0,1, D = 3; then, if there are N_S = 5 sinks in the network, the maximum number of nodes is about 250.

3.2.4 Actuators

Both the single-sink and multiple-sink networks reviewed above do not include the presence of actuators, namely devices able to manipulate the environment rather than observe and measeure it. WSANs are composed of both sensing and actuators nodes (see Figure 3.3).

The inclusion of actuators doesn’t represent a simple extension of a WSN. In fact from the communication protocol point of view the data-flow must go to the opposite direction in this case:

when sensors provide data the protocols should be able to manage many-to-one communications, and one-to-many when the actuators need to be controlled. The complexity of the protocols in this case is even greater.

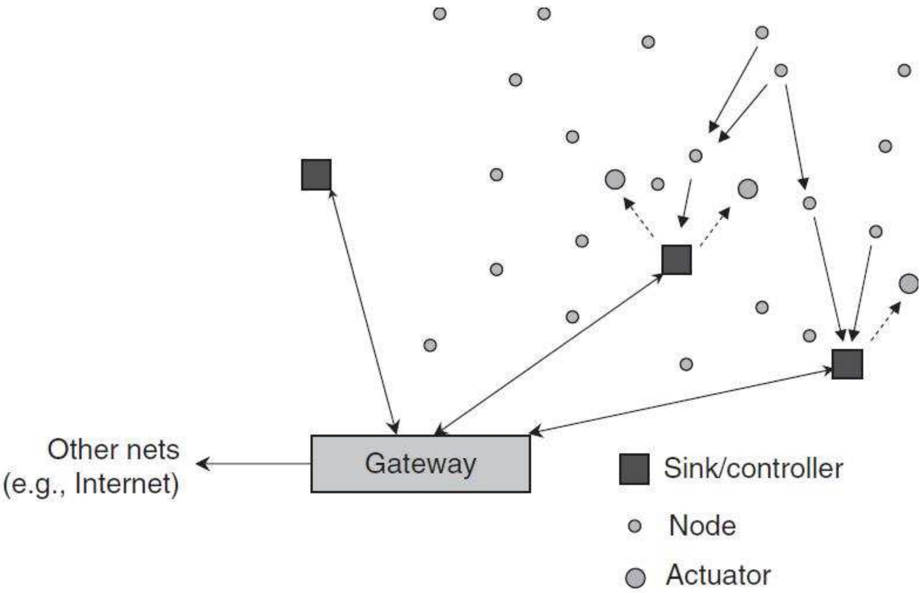


Figure 3.3 - WSAN

3.3 Wireless sensor network standards

The main value of wireless sensor networks is their low price. To achieve the economies of scale needed to reach a large market and facilitating the volume production minimizing the cost of components, the development of a standardized communication protocol is fundamental. Thus products from many manufacturers may operate together. This synergy will encourage their use avoiding the proliferation of proprietary and incompatible protocols..

The IEEE 802 Local and Metropolitan Area Network Standards Committee (LMSC) recently created Working Group 15 to develop a set of standards for WPANs [BGH00].

To deal with the need for low-power and low-cost wireless networking the IEEE New Standards Committee (NesCom) officially funded a new task group in Working Group 15 to begin the development of a standard for Low-Rate WPANs (LR-WPANs), called 802.15.4 (see Fig. 3.4 for more details).

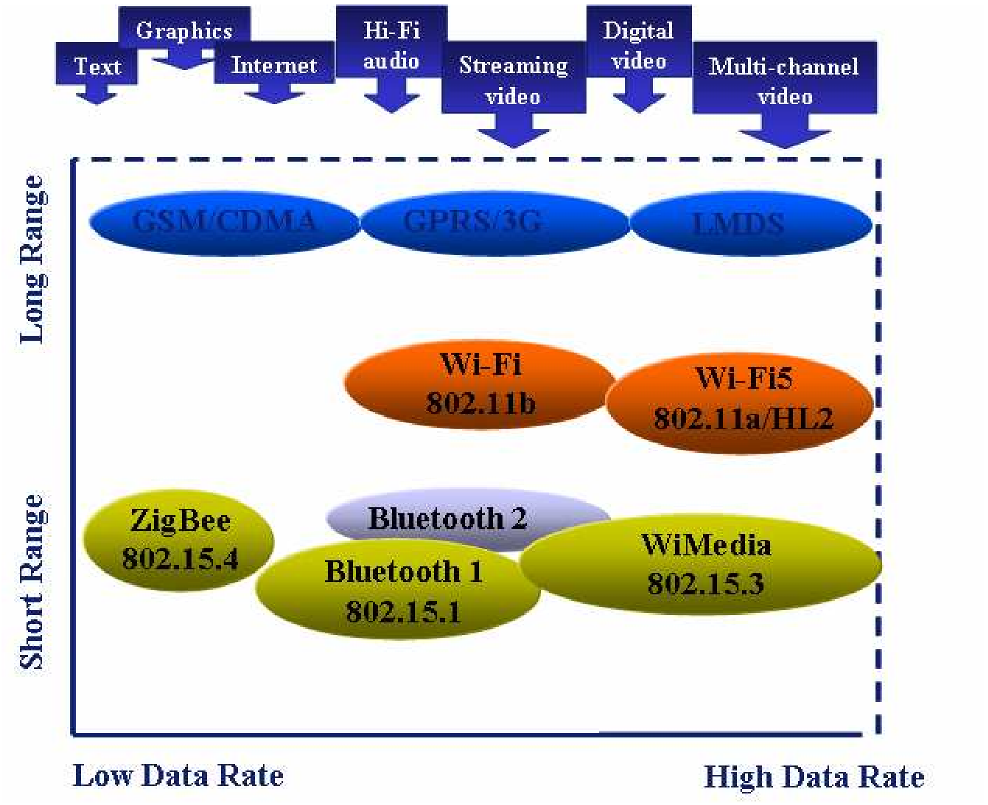


Figure 3.4 - 802 Standards' Wireless Space (source ZigBee Alliance)

The goal of this group was to provide a standard having ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive, fixed, portable, and moving devices [IEE03].

The main target of Task Group 4, as for all IEEE 802 wireless standards, was limited to the creation of specifications of the Physical (PHY) layer and Media Access Control (MAC) sub-layer of the Data Link Layer in the International Standards Organization (ISO) Open Systems Interconnection (OSI) reference model. In May 2003 the 802.15.4 standard was approved.

3.3.1 The IEEE 802.15.4 low-rate wpan standard

As noted in the previous paragraph, the scope of the IEEE 802.15.4 task group, as defined in its original Project Authorization Request, is to "define the PHY and MAC specifications for low data rate wireless connectivity with fixed, portable and moving devices with no battery or very limited battery consumption requirements typically operating in the Personal Operating Space (POS) of 10 meters."

Moreover the purpose of the project is "to provide a standard for ultra low complexity, ultra low cost, ultra low power consumption and low data rate wireless connectivity among inexpensive devices. The raw data rate will be high enough (maximum of 200 kbps) to satisfy a set of simple needs such as interactive toys, but scaleable down to the needs of sensor and automation needs (10 kbps or below) for wireless communications." [Mid00]

The maximum and minimum raw data rates were later raised respectively to 250 and 20 kb/s.

This diverse set of goals requires the IEEE 802.15.4 standard to be extremely flexible.

The IEEE 802.15.4 standard supports a large variety of possible applications in the POS Unlike protocols such as IEEE 802.11 that are designed for a single application.

The possible applications vary from those requiring high data throughput and low latency to those requiring very low throughput and able to tolerate significant message latency.

The IEEE 802.15.4 standard supports peer-to-peer and star connections, and is able to support a wide variety of network topologies. When security it is required that is entrusted to the AES-128 algorithm (see [Nis01] for more information about AES).

The standard includes optionally *beacons* (see Appendix A), with a variable beacon period that is a binary multiple of 15.36 ms, up to a maximum of 15.36 ms × 2^{14} = 4 minutes and 11.65824 seconds, thus that the optimum trade-off can be made between message latency and network node power consumption. When applications have *duty cycle* (see Appendix F) limitations the beacons can be omitted as, for example, may happen on networks in the 868 MHz band, which has law limits on node duty cycle, or systems that require nodes with constant listening mode.

The channel has a contention based access, the mechanism use a carrier sense multiple access with collision avoidance (CSMA-CA), if beacon is used it will be followed by a contention access period (CAP) for devices attempting to gain access to the channel, the length of the CAP is a fraction of the period between beacons.

The CAP may be limited to a fixed time of approximately 2 ms by a “battery life extension” mode.

When an application requires low message latency, the standard employs the optional guaranteed time slots (GTSs), which reserve channel time for devices without follow the CSMA-CA access mechanism.

A 16-bit address field is used to address the devices, meaning that up to (2^8 - 2) × (2^8 - 2) = 64,516 logical addresses (two values in each byte are reserved);

Therefore the standard also includes the ability to send messages with 64-bit extended addresses, allowing a sufficient number of devices for any application to be placed in a single network.

The messages can be fully acknowledged and in this case each transmitted frame (excepted the beacons and the acknowledgments themselves) may receive an explicit acknowledgment.

The overhead introduced with explicit acknowledgments is usually acceptable given the low data throughput typical of wireless sensor networks and the results is a reliable protocol.

Moreover the acknowledgments may optionally support the passive acknowledgment techniques, used in some ad hoc routing schemes, for example, the gradient routing (GRAd) algorithm (discussed later in this chapter).

Several features is designed to minimize power consumption are incorporates in the IEEE 802.15.4 standard.

Besides the use of long beacon periods and the battery life extension mode, the active period of a beaconing node can be drastically reduced (according to a powers of two), allowing the node to sleep within two beacons.

One important goal in the design of the IEEE 802.15.4 was the coexistence with other device and services using the same unlicensed bands.

As evidence the dynamic channel selection is implemented in the protocol, so if an interference from other services appear on a channel used by an IEEE 802.15.4 network, the network coordinator (PAN coordinator) scans the other available channels to find a the suitable channel.

In this scan, The coordinator obtains a measure of the peak energy present in each channel and then uses this information to select a free channel.

This channel selection scan can also be used prior to the establishment of the network or even prior to each frame transmission (except beacon or acknowledgment frames). Each network node must complete two clear channel assessments (CCAs) as part of the CSMA-CA mechanism to ensure the channel is unoccupied prior to transmission.

A link quality indication (LQI) byte is appended to each received frame by the PHI layer before it is sent to the MAC layer. This information may be used by receiving nodes for several purposes, at the discretion of the network designer and according to application needs.

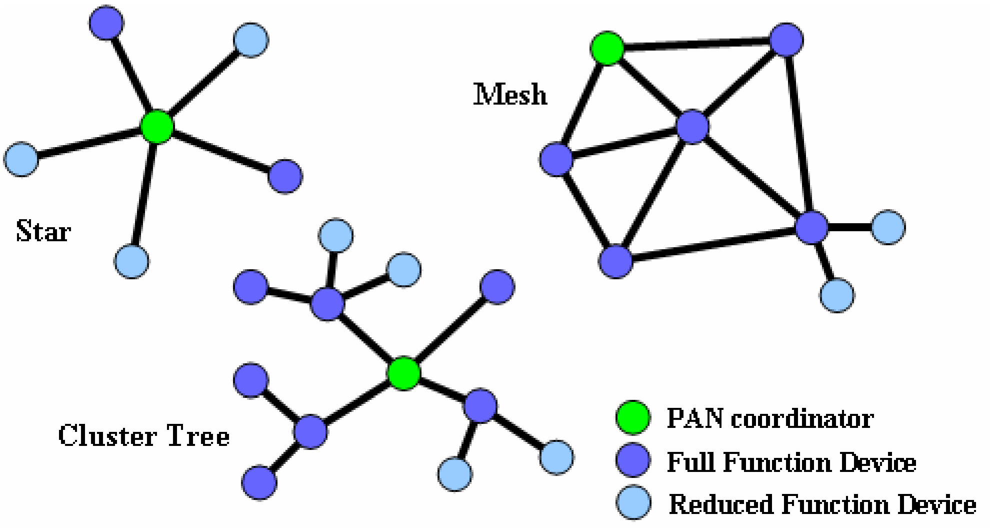


Figure 3.5- Network topologies and node types

For example, the LQI can be used as an indication of channel noise, perhaps leading to a dynamic channel selection process and move to another free channel or it can be used for power control of its own transmitter (assuming a symmetrical channel). It may be also used as part of a network routing algorithm based on link quality between network nodes or to estimate the location of each network node relative to its peers.

The LQI may be generated indifferently from a signal level determination, a signal-to-noise determination, or a combination of the two. This enables received signal strength indication (RSSI) and signal quality estimators to be used together.

Although a byte is reserved for the LQI, to ease the burden on developers that do not desire to make use of it (appropriate for some applications), the IEEE standard specifies that at least eight unique values shall be used in the LQI, including 0 × 00 and 0 × FF are to be associated respectively with the lowest and highest quality 802.15.4 signals detectable by the receiver.

To maximize the utility of the IEEE 802.15.4 tried to balance the desire to enable small, low-cost, and low-power network nodes with the needs to produce a standard that met a wide variety of on-field applications.
The resulting standard includes three types of network node functionality:

- **PAN coordinator**. The PAN coordinator is the node that initiates the network and is the controller of the network. The PAN coordinator may transmit beacons and can communicate with all the device in range. Depending on the network design, it may have memory sufficient to store information on all devices in the network, and must have memory sufficient to store routing information as required by the algorithm employed by the network.

- **Coordinator**. The coordinator may transmit beacons as the PAN coordinator and can communicate directly with any device in range. A coordinator may become or be promoted to PAN coordinator and start a new network.
- **Device**. A network device does not beacon and can directly communicate only with a coordinator or PAN coordinator.

These three functions are to be encapsulated into two different device types:

- **Full function device** (FFD)). An FFD can operate in any of the three network roles (PAN coordinator, coordinator, or device). It must have sufficient memory to store routing information as required by the algorithm employed by the network.

- **Reduced function device** (RFD). An RFD is a very low cost device, with minimal memory requirements. It can only function as a network device.

Wireless light switch is a typical example of a RFD. It must be as inexpensive to produce as possible, and has limited functional requirements. The light itself, however, may be the archetypical FFD because it can be more expensive, has access to mains power, and can have additional network functions as a more permanent feature of the building [Cal06].
The IEEE 802.15.4 standard, as said before, supports multiple network topologies.
In the standard, two network types are discussed: star networks and peer-to-peer networks. In the star network, the master device is the PAN coordinator (FFD node), and the other network nodes may either FFDs or RFDs.

In the peer-to-peer network, FFDs are usually used, one of them is the PAN coordinator. RFDs may be used in a peer-to-peer network, but they can only communicate with a single FFD belonging to the network, and so do not have a real “peer-to-peer” communication.

Similar to all IEEE 802 wireless standards, the IEEE 802.15.4 standard standardizes only the physical and medium access control (MAC) layers.

In fact the IEEE 802.15.4 standard incorporates two physical layers:

- The lower band: the 902–928MHz, for most of the Americas and pacific lands, 868.0–868.6 MHz (for Europe),

- The upper band: 2.400–2.485 GHz (worldwide with marginal differences in the band boundary)

The channel numbers and their center frequencies are defined as follows:

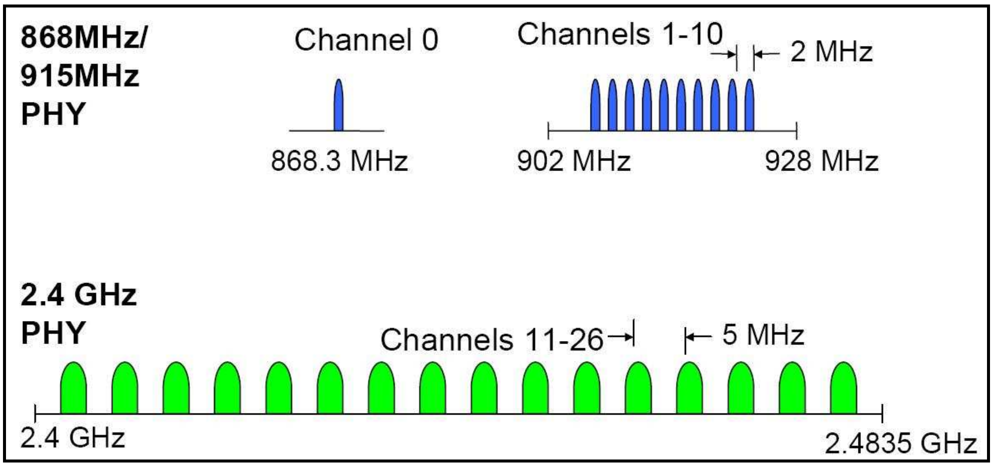


Figure 3.6- 802.15.4 channels (from ZigBee Alliance)

FC = 868.3 Mhz, for k = 0

FC = 906 + 2 (k-1) Mhz, for k = 1,2,…,10

FC = 2405 + 5 (k-11) Mhz, for k = 11,12,…,26

3.4 Protocol layers

As noted before, the IEEE 802.15.4 standard incorporate two distinct layers, the physical (usually simply called PHY) and the medium access control (MAC) layer.

However, to easily build an application without the need of a low level knowledge about the node structure, at least two more layers are required: the Data-link layer and Network layer. Thus a Alliance between some of the major industry was born to promote a 802.15.4 based standard containing the two more layers (see fig. 3.6 and 3.10).

The ZigBee standard will be discussed later in this chapter, now we will focus on the two IEEE 802.15.4 layers.

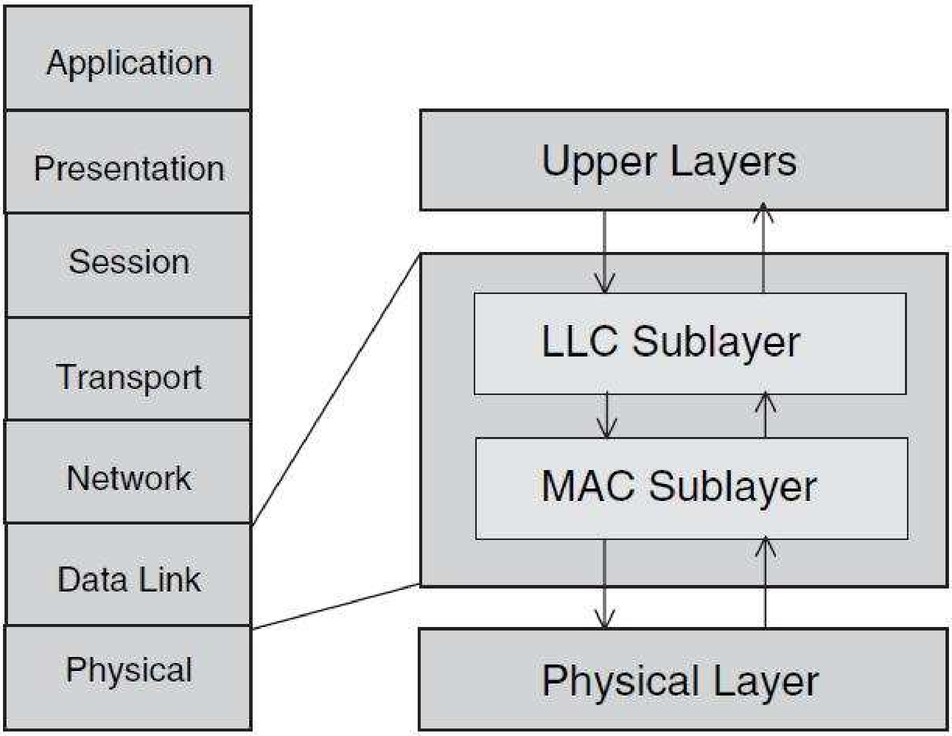


Figure 3.7 - OSI Data link layer architecture

3.4.1 The physical (PHY) layer

The physical layer (PHY) of the reference model specifies the network interface components, their parameters, and their operation.

Moreover, to support operation of the MAC layer, the PHY layer includes a variety of features, such as receiver energy detection (RED), link quality indicator (LQI), and clear channel assessment (CCA).

Parameter	2.4-GHz PHY	868/915-MHz PHY
Sensitivity @ 1% PER	-85 dBm	-92 dBm
Receiver maximum input level	-20 dBm	
Adjacent channel rejection	0 dB	
Alternate channel rejection	30 dB	
Output power, lowest maximum	-3 dBm	
Transmission modulation accuracy	EMV < 35% for 1000 chips	
Number of channels	16	1/10
Channel spacing	5 MHz	NA(Single channel)/2 MHz
Transmission rates	Date rate 250 kbps	20/40 kbps
Symbol rate	62.5 kilosymbols/sec	20/40 kilosymbols/sec
Bit per symbol	4	1
Symbol period	16 µs	49 µs/24 µs
Chip rate	2 megachips/sec	300/60 kilochips/sec
Chip modulation	O-QPSK with half-sine pulse shaping (MKS)	BPSK with raised cosine pulse shaping
Chip pseudo-noise sequence	32	15
RX-TX and TX-RX turnaround time	12 symbols	

Table 3.2 IEEE 80215.4 PHY Layer Main Parameters

The PHY layer is provided by a wide range of operational low-power features, including low-duty-cycle operations, strict power management, and low transmission overhead [SMZ07]. These parameters are listed in Table 3.2.

The two PHY bands, viewed in the paragraph 3.3.1, employ a form of direct sequence spread spectrum (DSSS).

The DSSS is one of the spread spectrum modulation techniques, and as all these kind of techniques, use a carrier signal that occur on the full device’s transmitting bandwidth (the so called spectrum) thus the modulation occupy more bandwidth than the information signal itself.

DSSS provides a higher data rates and shorter delays than FHSS (the frequency hopping technique also used in wireless transmission see appendix A for more information about FHSS), because the device don't spend time retuning.

The spread-spectrum techniques are resistant to interference, signals that stay in one narrow area (and don’t move), but they don’t do as well when other spread spectrum systems are operating nearby.

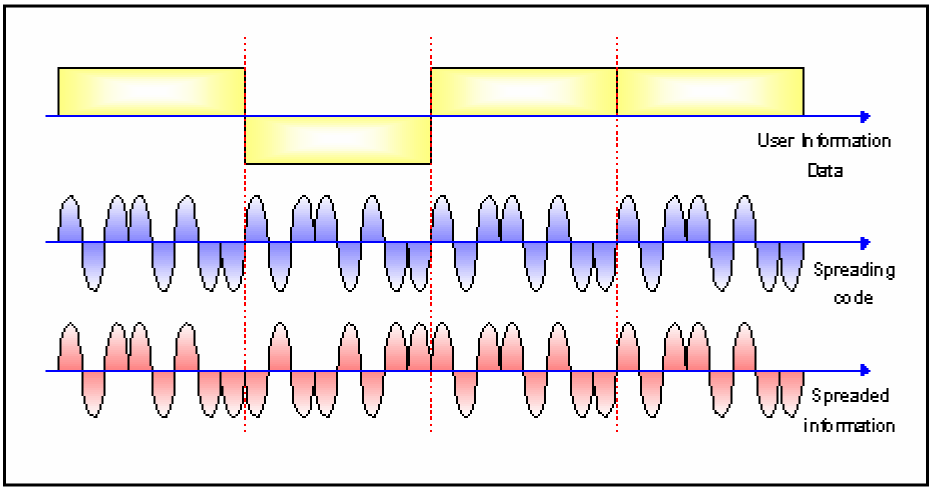


Figure 3.8- DSSS modulation technique

In our case DSSS is resistant to interference via the spreading function that concentrate the desired signal but spread and dilutes any interfering signal, however few nearby FHSS systems are sufficient to cripple a DSSS system, on the other hand, because a DSSS system is transmitting on every frequency in the band, a nearby FHSS system will be unable to find any clear channel to use.

FHSS usually degrades more gracefully than DSSS in the presence of interference but neither works well when competing at close range.

DSSS transmission is generated multiplying the data by a noise signal generated as a pseudorandom sequence of 1 and -1 values. This noise signal has a much higher frequency than the information signal.

Direct-sequence spread-spectrum transmissions multiply the data being transmitted by a noise signal.

The noise-like signal can be used by receiver to reconstruct the original data, by multiplying it by the same pseudorandom sequence (because 1 × 1 = 1, and −1 × −1 = 1). This process is known as de-spreading.

To work correctly, the transmit and receive sequences must be synchronized via some sort of timing process.

Application	***Frequency Band Used***
AM radio	535–1635 kHz
Analog cordless telephone	44–49 MHz
Television	54–58 MHz
FM radio	88–108 MHz
Television	174–216 MHz
Television	470–806 MHz
Wireless data	700–720 MHz
Cellular	806–890 MHz
Digital cordless	900 MHz
Personal communications	900–928 MHz
Nationwide paging	929–932 MHz
Satellite telephone uplink	1610–1625.5 MHz
Personal communications	1850–1990 MHz
Satellite telephone downlink	2.4835–2.5 GHz
IEEE 802.11b/g wireless LANs	2.4 GHz
IEEE 802.15.4/Zigbee alliance	2.4 GHz
IEEE 802.16/WiMax	2–66 GHz
IEEE 802.11a wireless LANs	5 GHz
Large dish satellite TV	4–6 GHz
Small dish satellite TV	11.7–12.7 GHz
Wireless cable TV	28–29 GHz

Table 3. 3 - Common Wireless Applications and Their Frequencies

If a second transmitter use the same channel but with a different noise sequence, the de-spreading process results in no processing gain for that signal, allowing multiple DSSS transmitters to share the same channel within the limits of the cross-correlation properties of their sequences. In table 3.3 can be seen the frequency commonly used by wireless applications.

3.4.2 Packet structure

The packet structure of the IEEE 802.15.4 PHY layer is shown in fig. 3.9. The first field of this structure contains a 32-bit preamble used for symbol synchronization. The next field contain a 8-bit value used for frame synchronization and represent a start of a packet delimiter. The PHY header (8-bits) field specifies the length of the PHY service data unit (PSDU) that can carry up to 127 bytes of data.

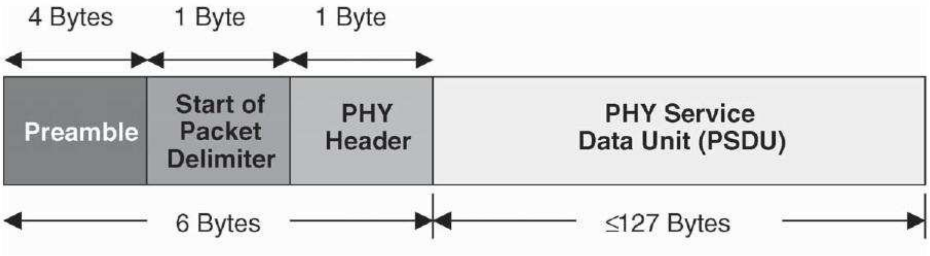


Figure 3.9- 802.15.4 PHY-layer packet structure

The total packet transmission time is about 4,3 ms at 250kbps or 52 ms at 40kbps (the two typical bands).

3.5 The medium access control (MAC) layer

As already mentioned the need to conserve energy is the most critical issue in the design of MAC layer protocol for WSNs.

Several factors may contribute to energy waste such as idle listening, packet collisions, and overhearing.

The media access regulation requires the exchange of control and synchronization information between the competing nodes. The exchange of a large number of control and synchronization packets may result in a significantly increase of energy consumption. On the other hand long periods of idle listening may decrease network throughput increasing energy consumption.

In some cases the energy wasted by idle listening is equal to one-half of the total energy consumed by a sensor during its lifetime. [Bou08]

Another source of significant energy waste is the retransmission of colliding packets. Moreover a high number of collisions may lead to significant performance degradation.

The excessive overhearing yet causes a node to receive and decode packets intended for other nodes increases energy consumption and degrading the network throughput.

The main objective of a WSN MAC-layer protocols is to reduce such energy waste discussed above.

These protocols can be categorized into two main groups:

- **schedule-based** MAC-layer protocols: these protocols are a class of deterministic protocols in which the channel access is based on a schedule. Channel access is limited to one sensor node at a time. This is achieved by a resources pre-allocation to individual nodes.

- **contention-based** MAC-layer protocols: these protocols avoid pre-allocation of resources. Instead, a single radiochannel is shared by all nodes and allocated on demand. However each simultaneous attempts to access the communications channel results in collision. The main objective of contention-based MAC layer protocols is to minimize the occurrence of collisions, rather than completely avoid them.

To reduce energy consumption, these protocols differ in the mechanisms used to reduce the possibility of a collision while minimizing overhearing and control traffic overhead.

Resolving collisions is usually achieved using distributed, randomized algorithms to reschedule channel access among competing sensor nodes. The basic approach used to reduce overhearing is to force nodes into a sleep state when they become inactive. [SMZ07]

Communication between wireless sensor nodes is usually achieved by a unique channel. Usually only a single node can transmit a message at any given time using this channel, so the shared access of the channel requires a protocol among the nodes. The MAC protocol is designed to regulate access to the shared wireless medium such that the performance requirements of the application are satisfied.

From the perspective of OSI Reference Model, the MAC functionalities are provided by the lower sublayer of the data link layer (DLL).

The higher sublayer of the DLL is referred as the logical link control layer (LLC). The presence of the LLC sublayer allows support for several MAC options, depending on different characteristics as network topology used, type of communication channel, quality of service requirements.

The MAC sub layer resides directly above the physical layer (see fig. 3.6 and 3.10) and perform the following three functions [SMZ07]:

- Assembly of data into a transmitting frame by appending a header field containing addressing information and a trailer field for error detection
- Disassembly of a received frame to extract addressing and error control information to perform address recognition and error detection and recovery
- The regulation of access to the shared transmission medium

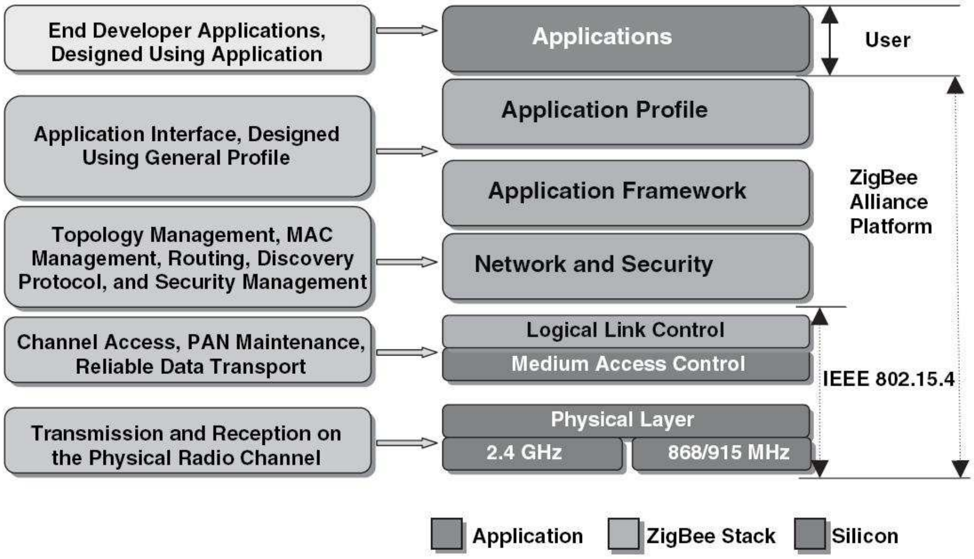

End Developer Applications, Designed Using Application
Application Interface, Designed Using General Profile
Topology Management, MAC Management, Routing, Discovery Protocol, and Security Management
Channel Access, PAN Maintenance, Reliable Data Transport
Transmission and Reception on the Physical Radio Channel
Applications
Application Profile
Application Framework
Network and Security
Logical Link Control
Medium Access Control
Physical Layer
2.4 GHz
868/915 MHz
User
ZigBee Alliance Platform
IEEE 802.15.4
Application
ZigBee Stack
Silicon

Figure 3.10- Stack Reference Model and their relative tasks

The LLC sub layer of the DDL provides a direct interface to the upper layer protocols. Its main objective is to shield the upper layer protocols from the characteristics of the underlying physical network. The use of the LLC sublayer is very limited as interoperability is usually achieved by other network layer protocols.

The IEEE 802.15.4 MAC-layer specification is designed to support a large variety of industrial and home applications for control and monitoring as previously discussed (see paragraph 2.2). These applications usually require low to medium data rates and moderate average delay and high flexibility. moreover, the complexity and implementation cost of the IEEE 802.15.4 standard compliant devices must be low to minimize energy consumption and enable large scale production of these devices.

To achieve these goals IEEE 802.15.4 MAC-layer specification embeds in its design several features for flexible network configurations and low-power operations.

These features include [SMZ07]:

- Various network topologies and devices support
- Optional super-frame structure to control the network devices' duty cycle
- Direct and indirect data transmissions
- Contention- based and schedule-based MAC methods
- Beaconed and non-beaconed modes of operation (beacon mode uses a super-frame structure to coordinate access to the medium. Support for contention-based access and guaranteed time slots allocation; in non-beaconed mode, the protocol uses an unslotted CSMA/CA based access scheme.)
- Efficient energy management schemes for an extended battery life that includes adaptive sleep for period of time over multiple beacons
- Flexible addressing scheme to support the deployment of large-scale networks (over 65,000 nodes per network)

Based on the logical devices types seen in paragraph 2.4.1, a IEEE 802.15.4 wireless personal area network can be organized in one of three possible topologies: star, mesh (peer-to-peer), or cluster tree. The three network configurations are depicted in figure 3.5. The star network topology supports a single coordinator, with up to 65,536 devices.

In this topology configuration, one of the FFD-type devices assumes the role of network coordinator. All other devices act as end devices.

The selected coordinator is responsible for initiating and maintaining all the end devices on the network.

The end devices can only communicate with the coordinator. The mesh configuration allows path formation from any source device to any destination device, using tree and table-driven routing algorithms.

distance vector routing (AODV) and Internet Engineering Task Force (IETF).

In the mesh topology the radio receivers of the PAN coordinator and the routers must be always active.

Cluster tree networks enable a peer-to-peer network to be formed using multihop routing.

A cluster tree network is self-organized and supports network redundancy to achieve a high degree of fault tolerance and self-repair. The cluster tree topology fits latency-tolerant applications.

The cluster can be significantly large, comprising up to 255 clusters of up to 254 nodes each (for a total of 64.770 nodes).

The routing algorithm employs a simplified version of the on-demand

Any FFD can be a coordinator. The PAN coordinator, chosen from one of the coordinators, build up the first cluster and assigns to it a cluster identity (CID) of value zero. All other clusters are then formed with a designated cluster coordinator for each cluster.

Each PAN is uniquely identified by a 16-bit identifier. A PAN coordinator is designated as the controller of the WPAN.

Every network has exactly one PAN coordinator, selected from within all the coordinators of the network.

A coordinator is a device configured to support advanced network functionalities including:

- Managing a list of all associated network devices
- Exchanging data frames with network devices and a peer coordinator
- Allocating 16-bit short addresses to network devices
- Generating beacon frames on a periodic basis (used to announce the PAN identifier, and other network and device parameters.)

Must be noted the MAC layer offers channel scan capability and not only and association/disassociation functionalities. This scan procedure work on several logical channels by sending a beacon request message and listening or just listening in case of a passive scan (RFD nodes) for beacons to locate other PANs coordinators.

The higher protocol’s layers decide which PAN to join and ask the MAC layer to provide the association procedure for the selected PAN/channel. The MAC layer send a join request to one of the network coordinators and if accepted the node receives his address that it may use for all communication purposes.

3.5.1 Frame and super-frame structure

The MAC layer provides four frame form structures, one for each type of message that can be sent:

- **Data frame**: provides up to 104 byte data payload capacity, include a sequence numbering to ensure that packets are tracked and a Frame Check Sequence (FCS) validates error-free data.

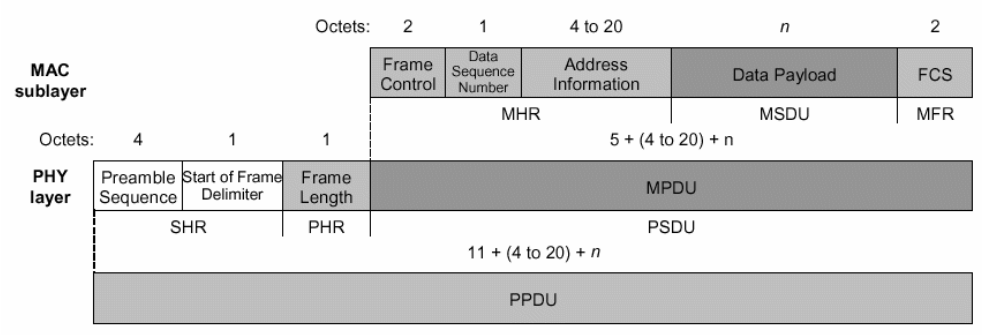


Figure 3.11- Data Frame Format

- **ACK frame**: is a short packet that provides active feedback that packet was received without error

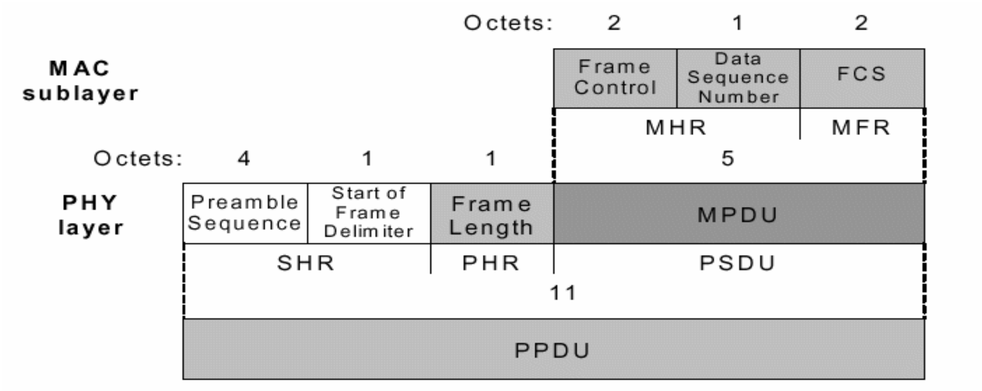


Figure 3.12 - ACK Frame format

- **Command frame**: allow remote control/configuration of client nodes and a centralized network manager to configure individual clients.

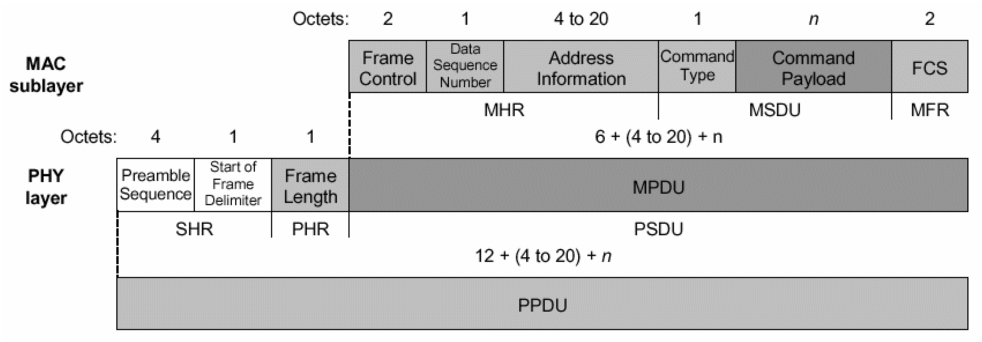


Figure 3.13- MAC Command frame format

Command Frame Identifier	Command	RFD	
		TX	RX
00000001	Association request	X	
00000002	Association response		X
00000003	Disassociation notification	X	X
00000004	Data request	X	
00000005	PAN ID conflict notification	X	
00000006	Orphan notification	X	
00000007	Beacon request		
00000008	Coordinator realignment		X
00000009	GTS request		

Table 2.4 - MAC Commands

- **Beacon data frame**: client devices can wake up only when a beacon is to be broadcast, listen for their address, and if not heard, return to sleep. Beacons are important for mesh and cluster tree networks to keep all of the nodes synchronized without requiring nodes to listening for long periods of time and consume battery energy.

The frames are depicted in the fig 3.11-3.14
As already mentioned the IEEE 802.15.4 MAC defines an optional super-frame structure. When used it is initiated by the PAN coordinator. Furthermore, its format is decided by the coordinator.

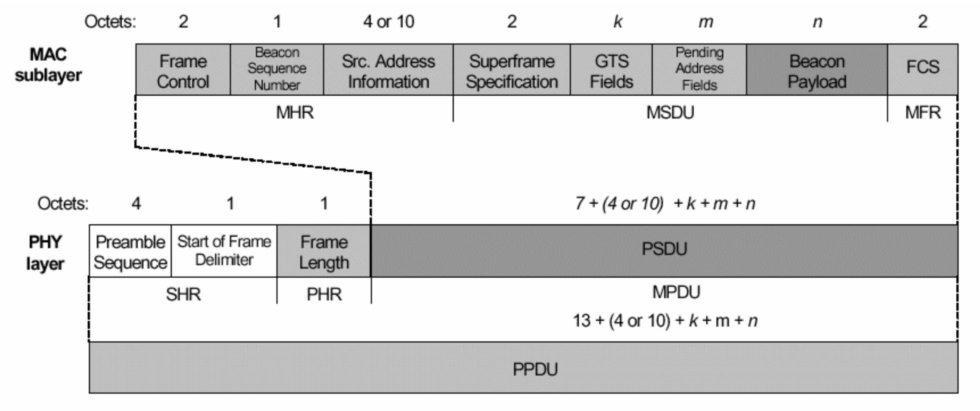


Figure 3.14 - Beacon data frame format

As Figure 3.15 shows, the super-frame is divided into 16 equally sized slots.

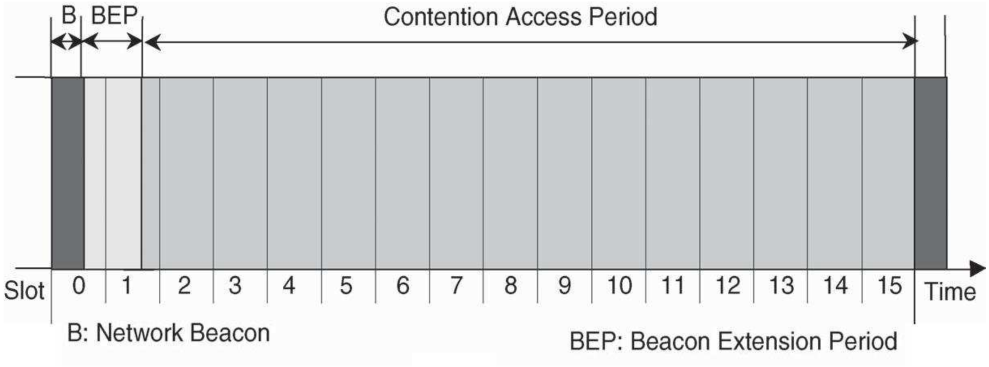


Figure 3.15 - Super-frame structure

The first time slot of each super-frame is always used to transmit the beacon. The beacon has synchronization function for the devices, it identifies the PAN and describe the super-frame structure itself.

The remaining time slots are used by competing devices, through a CSMA-CA based protocol, for communications during the contention access period. All communications between devices must be completed by the end of the current CAP and the beginning of the next network beacon.

The PAN coordinator may dedicate groups of contiguous time slots of the active super-frame to these applications with specific latency and bandwidth requirements. These slots are named guaranteed time slots (GTSs) and their number cannot exceed seven. However a GTS may occupy more then one time slot. Together the GTSs form the contention free period (CFP).

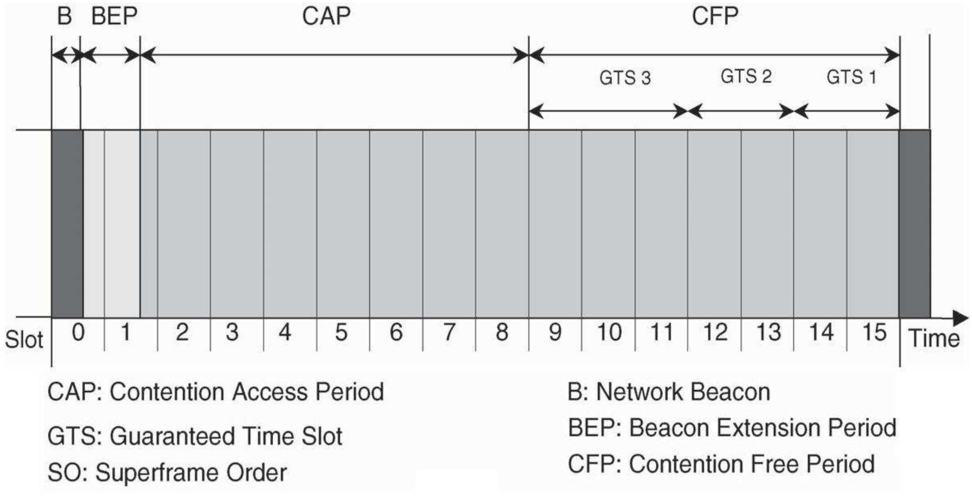

B
BEP
CAP
CFP
GTS 3
GTS 2
GTS 1
Slot
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time
CAP: Contention Access Period
GTS: Guaranteed Time Slot
SO: Superframe Order
B: Network Beacon
BEP: Beacon Extension Period
CFP: Contention Free Period

Figure 3.16 - Super-frame with GTSs

The CFP always appears at the end, of the active super-frame and starts at a slot boundary immediately following the CAP, as depicted in Figure 3.16. The CAP time slots still remain for contention-based access between devices and new devices trying to join the network.

All communication transactions using contention-based access and GTS-based access must respectively complete before the end their associated CAP and CFP.

Network devices can send requests for GTS allocation during the CAP period to reserve contiguous time slots, either the receive (from the coordinator) or transmit (to the coordinator) data.

Devices can switch off their power and go into a sleep mode when have no data to send. However devices are must to remain active, during their allocated GTSs but are allowed to go into a sleep mode during the other GTSs periods.

The coordinator may also send a super-frame containing both an active and an idle period to reduce energy consumption, as shown in figure 3.17.

The active period, always composed by the 16 time slots, contains the frame beacon, the CAP time slots and the CAP slots when applicable. The inactive period defines a configurable time period during which all network nodes, including the coordinator, can go into a sleep mode switching off their power and set a wake up timer to the next beacon frame (just before it).

Summarizing the general MAC frame format is composed of three basic components: a header, a payload, and the footer.

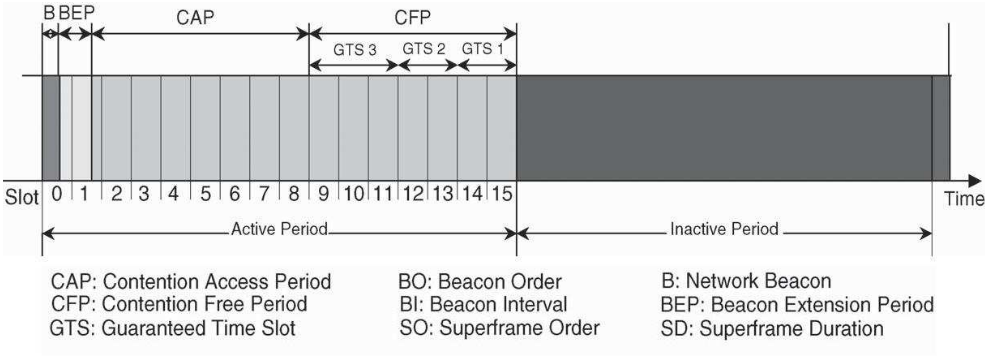


Figure 3.17 - Super-frame with inactive period

The MAC header contains a frame control field and the address field. The control field carries the frame type and other information necessary for network control and operation. The address specifies the source PAN identifier and source node address, the destination PAN identifier and address.

The MAC payload contains the data frame to be exchanged between the communicating devices. The MAC footer contains the frame check sequence field and is also used to detect frame errors.

3.5.2 The association request and response command formats

The association command is part of the MAC association services and is formed by association request and response illustrated in Figure 3.18.

The capability information field of the association request supply information about many questions regarding the device that requested to join the network:

- The device is a PAN coordinator, the alternate PAN coordinator field is set to zero if the device cannot act as a PAN coordinator.
- Is this node an FFD or an RFD device, if the device type field is set to one, the device is an FFD.
- The device is battery powered or connected to a main power source, for battery powered nodes, the power source field is set to zero.
- The device keep its receiver in ON mode all the time or turn off the receiver and go to power-saving mode when the device is idle. The receiver is ON when idle field is set to zero if the receiver is turned off during idle mode. The value of this field comes from the MAC attribute *macRxOnWhenIdle* and is equal to FALSE if the receiver is turned off during idle mode.

- The device want to have a new address after joining the network. If the device needs a short address, the allocate address field is set to one.

The PAN coordinator uses the association response command to accept or deny the association request from a node. If the coordinator has reached its maximum capacity it will be indicate in PAN capacity status.
If the association is accepted and the node also asked for a new short address, the short address is sent in the short address field of the association response.

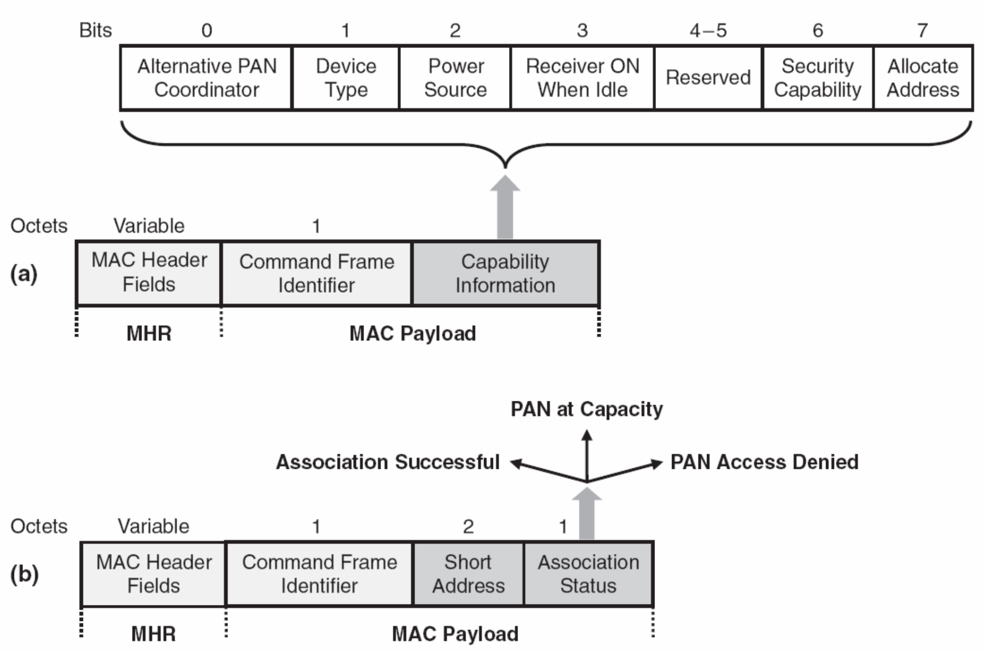


Figure 3.18 - The Association Request Command (a) and The Association Response Command (b)

3.5.3 The Disassociation Notification

The disassociation is a procedure that an associated node uses to notify the parent or the coordinator that the device itself wants to leave the network .

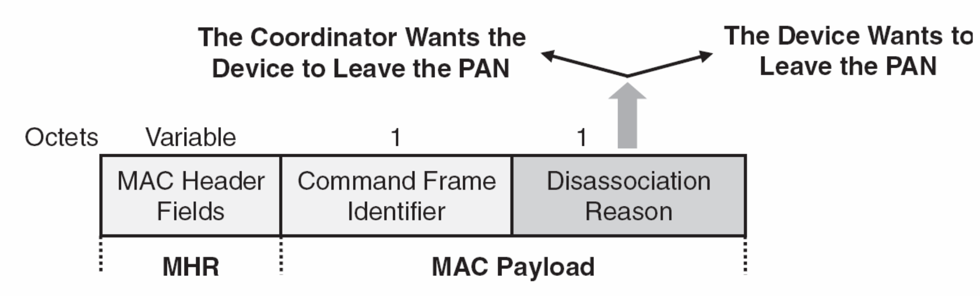


Figure 3.19 - MAC Disassociation Notification Command

The disassociation frame format is depicted in Figure 3.19. A device will leave a network based on either its own decision or the request of the parent/coordinator (for instance when the parent itself wants to leave the network).

3.5.4 Security

The security services specified by the IEEE 802.15.4 model provide support for infrastructure security and application data security. There are four kind of services:

- The first security service of provides support by preventing unauthorized parties from joining the network and allows a device to maintain a list of network trusted devices. This list is used by any network node to detect and reject messages from unauthorized devices.
- The second security service supports message integrity protection to prevent the tampering attempt of a legitimate data message from an authorized sender while the message is in transit (by any kind of intruder).
- The third security service provides the data confidentiality of e message. This is achieved implementing the a 128-bit key advanced encryption standard (AES) cryptographic algorithm.
- The fourth security service deals with sequential data freshness to prevent replay attacks, where an unauthorized party resend legitimate messages at a later time.

The MAC layer describes a variety of security suites, based on this four security services, each one offering a different set of security properties and guarantees. The MAC standard specify that the security is not enabled by default and the application must explicitly set the appropriate parameters to enable the desired security level.

3.6 ZigBee standard

ZigBee and IEEE 802.15.4 are standards-based protocols that provide the network infrastructure required for wireless sensor network applications. ZigBee is a trademark like Wi-Fi and WiMAX and its stack, shown in figure 3.20, only defines some functionalities in layers on top of the IEEE 802.15.4 standard.

The IEEE 802.15.4 standard has been adopted by the ‘ZigBee Alliance’ for wireless personal area network technology. “The Alliance is an association of hundreds of members from around the world, working together to enable the reliable and cost-effective networking of wireless devices for monitoring and control, based on an open global standard” [Kin05].

802.15.4 defines the physical and MAC layers, and ZigBee defines the network and application layers. Using the IEEE 802.15.4 specifications, allow the alliance to focus on the design issues.

3.6.1 The network layer (NWK APL)

ZigBee Alliance provides the network layer (NWK) and some applications, and differentiates between a usual node, a coordinator and a router. The only difference between the last two is based on the connection to some external network.

The NWK and addresses three main items via ZigBee Device Objects (ZDOs):

The role of discovery is, as the name suggests, to discover nodes and then they use unicast messages to inquire about the ZigBee coordinator’s or router address. This may also query about addresses of other associated devices. There is also a broadcast inquiry for the coordinator’s/router addresses.

Must be noted that there is a distinction between the MAC and the network addresses, clearly IP but the field is left open for any proposal.

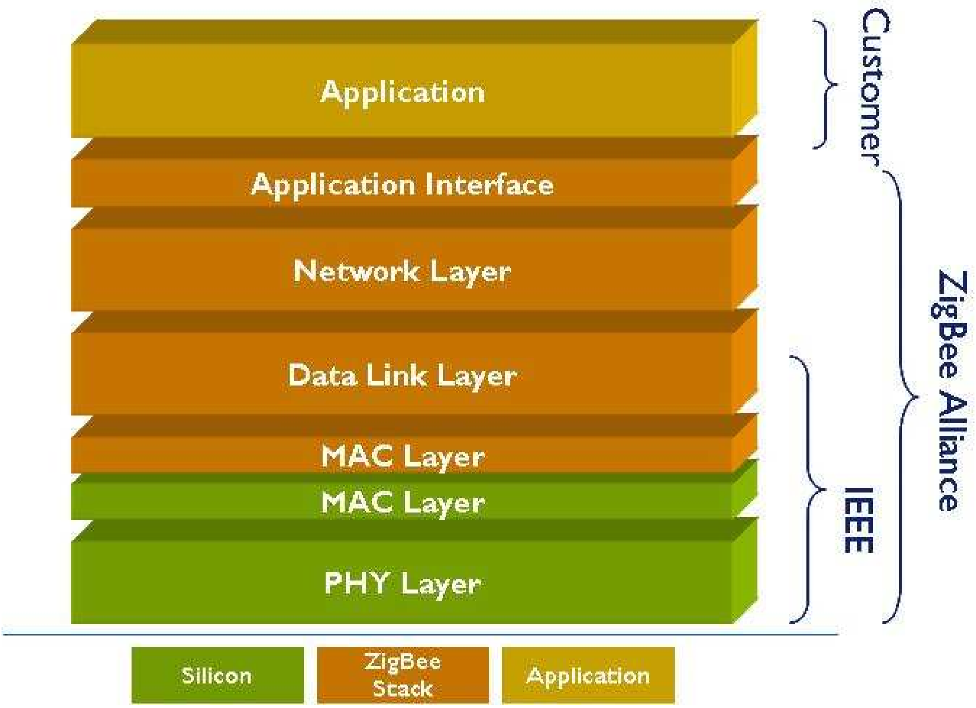


Figure 3.20- ZigBee stack architecture

- **Service discovery**
- **Security**
- **Binding**

The equivalent of the Address Resolution Protocol (ARP) is also supported in ZigBee by a similar mechanism: a broadcast with the network or the MAC address shall return the other missing one.

ZigBee use profiles like Bluetooth but is more evolved. A profile defines the applications running on top of a device where it also specifies the members and the possible actions. So it is a set of device requirements, collaborating to fulfill a role. An example could be a thermometer, a blood pressure probe, and a console together forming a patient monitoring application [LAD07].

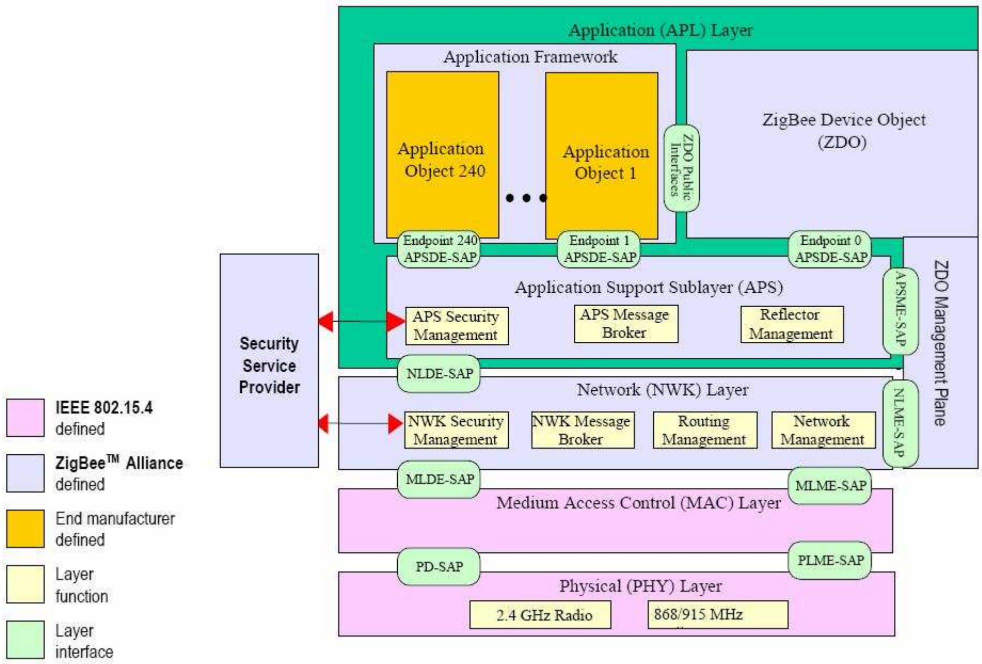


Figure 3.21- ZigBee extended architecture

As profiles play an important roles in ZigBee, the discovery on the other hand allow the locating procedure for some services via their profile identifiers.

The security services in ZDO have the role to authenticate and derive the necessary keys for data encryption. Thus ZigBee complements IEEE 802.15-4 for security.

The encryption key is used as in Bluetooth to authenticate and derive a shared secret, named ‘link key’. An initiator device and a responder have a pre-established trust. Three more steps follow this trust establishment: an exchange of test data, derivation of the link key and a confirmation.

The master secret shared between devices could be sent before with an out-of-band channel. It’s called a proximity authentication channel and is used in several similar protocols.

Another ZDO’s component is the network manager, implemented in the coordinator and it allow the selection of an existing PAN to interconnect. Furthermore it provides the creation of new PANs and implements also a routing algorithm between routers of different PANs that it has discovered.

The binding manager is last component and has the role to bind nodes to resources and applications and to bind devices to channels in order to calculate the remaining available bandwidth a coordinator can grant on the link.

3.6.2 The application layer

The application layer consists of the application support sub-layer (APS), the ZigBee device object, and the application-defined objects (see fig 3.21).

The responsibilities of the APS sub-layer include maintaining tables for binding devices together and forwarding messages between devices.

The ZDO can be thought as a special application object resident on all nodes. It has its own profile, referred to as the ZigBee device profile (ZDP) that can be accessed by user application and other ZigBee nodes.

The ZDO is responsible for device management, security keys and policies, including, but not limited to, defining the role of the device within the network, initiating and responding to binding requests, and establishing a secure relationship between network nodes.

The designer-defined application objects implement the actual applications according to the ZigBee-defined application descriptions.

3.6.3 ZigBee Versions from 2004 to PRO

In conclusion we can say that the main goal in developing ZigBee technology was to provide a standard for the operation of remote monitoring sensor devices and for this reason several features were added in the subsequent version of the ZigBee standard

The ZigBee 1.0 specification was ratified in December 2004, and is referred to as ZigBee 2004. Most manufacturer developed their ZigBee 1.0 compliant library during the 2005. In December 2006, the ZigBee 2006 specification was released, which was followed in October 2007 by the ZigBee 2007 and at the end of the same year by PRO version specification. Each new release adds to and improves functionality provided in previous versions of the specification.

The table below illustrates a high-level comparison showing the similarities and differences between the 2004, 2006, and 2007/PRO ZigBee versions.

	2004	**2006**	**2007**	**PRO**
Interference avoidance				
Coordinator selects best available RF channel/Network ID at startup time.	**Yes**	**Yes**	**Yes**	**Yes**
RF channel and/or Network ID can be changed during operation to address interference.			**Yes**	**Yes**
Automated/distributed address management				
Addresses automatically assigned using hierarchical, distributed scheme.	**Yes**	**Yes**	**Yes**	

Addresses automatically assigned using stochastic scheme				**Yes**
Group addressing				
Devices can be assigned to groups, which can be addressed with a single frame; thereby reducing network traffic for packets destined for groups.		**Yes**	**Yes**	**Yes**
Centralized data collection				
Low-overhead data collection by ZigBee coordinator supported	**Yes**	**Yes**	**Yes**	**Yes**
Low-overhead data collection by other devices supported under special circumstances (e.g. with Tree Routing).	**Yes**	**Yes**	**Yes**	**Yes**
Many-to-one routing allows the whole network to discover the aggregator in one pass.				**Yes**
Source routing allows the aggregator to respond to all senders in an economical manner				**Yes**
Security				
128-bit AES encryption with 32-bit Message Integrity Code (MIC)	**Yes***	**Yes**	**Yes**	**Yes**
Frame counters to assure message freshness	**Yes**	**Yes**	**Yes**	**Yes**
Security applied at the NWK layer by default, and supported at higher layers.		**Yes**	**Yes**	**Yes**
Key rotation prevents hacking of NWK key.		**Yes**	**Yes**	**Yes**
Trust Center operates on the ZigBee Coordinator to manage trust on behalf of network devices and act as central authority on which devices can join the network.				**Yes**
High Security mode supported, which is selectable by Trust Center policy, and requires Application Layer Link Keys, peer-entity authentication, and peer-to-peer establishment using Master Keys.				**Yes**
Trust Center can run on Coordinator or any other device in the network.				**Yes**
Network scalability				
Addressing algorithm supports networks with tens to hundreds of devices.	**Yes**	**Yes**	**Yes**	
Addressing algorithm supports networks with hundreds to thousands of devices.				**Yes**
Message size				
< 100 bytes, with exact size depending on services employed (e.g. security).	**Yes**	**Yes**		
Large messages, up to the buffer capacity of the sending and receiving devices (supported using Fragmentation and Reassembly			**Yes**	**Yes**

Standardized commissionino				
Standardized start up procedure and attributes support the use of commissioning tools in a multi-vendor environment.		**Yes**	**Yes**	**Yes**
Robust mesh networking				
Fault tolerant routing algorithms respond to changes in the network and in the RF environment.	**Yes**	**Yes**	**Yes**	**Yes**
Every device keeps track of its “neighbourhood”; thereby improving reliability and robustness.				**Yes**
Cluster Library support				
The ZigBee Cluster Library, as an adjunct to the stack, standardizes application behaviour across profiles and provides an invaluable resource for profile developers.		**Yes**	**Yes**	**Yes**

* AES in version 2004 is optional and not activate by default

Table 3. 5- ZigBee changes from 2004 to PRO version (source [Dai08])

About the backward compatibility the first ZigBee 1.0 original specifications were abandoned and the compatibility is not assured as we can see from the below list, while is required a backward compatibility from the 2007/PRO versions toward the 2006 specifications:

ZigBee 2007/PRO:

- Backward compatibility with ZigBee 2006 required.
- Backward compatibility with ZigBee 2004 not required.

ZigBee 2006

- Backward compatibility with ZigBee 2004 not required.

ZigBee 2004

- Original ZigBee version.

3.6.4 Brief comparison with other protocols

As previously noted ZigBee focuses on large scale monitoring applications in which nodes require a low data rate and very low power consumption.

ZigBee protocol can be used to connect the ZigBee nodes to be integrated with the IP networks. This approach enables remote sensing and controlling on the Internet.

Technologies such as the well known Wi-Fi target devices running applications that require large amounts of data to be transferred, thus the Wi-Fi devices require large amounts of battery power.

The Bluetooth technology is mainly a cable replacement among personal devices and it supports a lower bandwidth than Wi-Fi.

Both Wi-Fi and Bluetooth support a network sizes reasonably limited, while ZigBee can support up to 65536 nodes in a single network.

Furthermore ZigBee allows nodes to go in sleep mode, saving a considerable amount of energy. The bandwidth supported by ZigBee standard is much smaller than that of Wi-Fi and Bluetooth and for this reason it is only suitable for applications that require small amounts of data transmission.

Accordingly with its network size capability, ZigBee is suitable for large scale applications such as industrial control.

Wireless USB as the same target of Bluetooth and suffers from the same power problem similar to Wi-Fi with a small transmission range offered.

In conclusion Wi-Fi, Bluetooth and Wireless USB are not suitable for the same application domains as ZigBee (large scale monitoring and controlling applications).

On the other hand technologies such as Wibree, Z-Wave and EnOcean, made for similar market, suffer from the lack of standardization [Hos08].

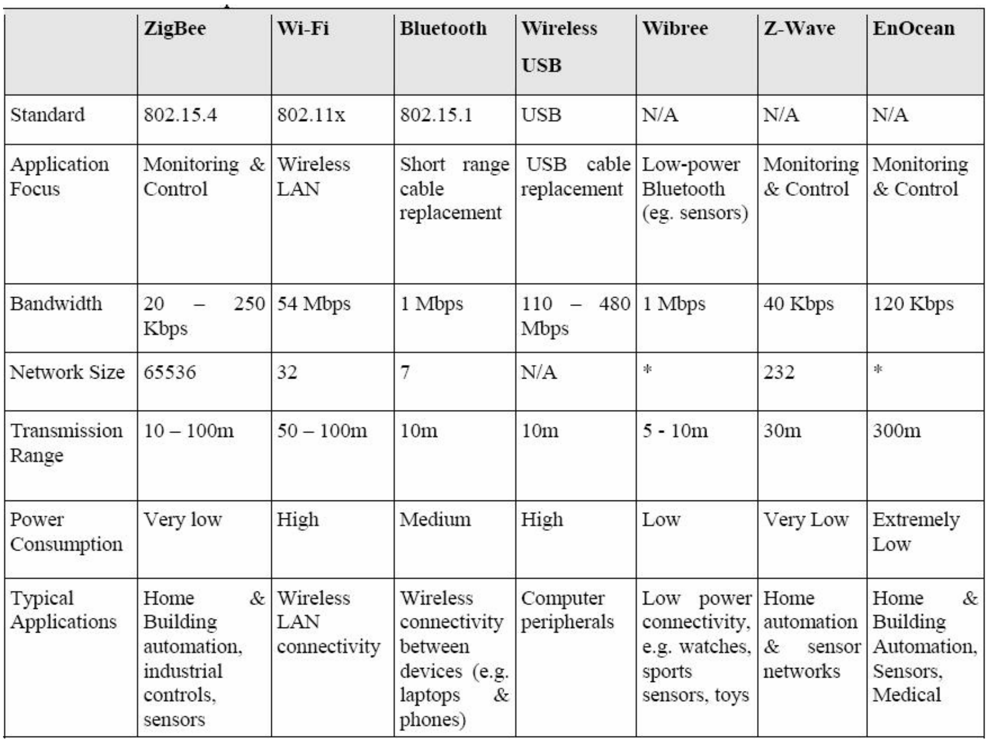
The Wibree technology, developed by Nokia, is a low-powered extension to Bluetooth. The main advantage of this technology is that it can be implemented using existing Bluetooth devices. Although it has a higher data transmission rate than ZigBee, it has a very limited range, which makes it unattractive for large-scale networks.

Z-Wave technology has been developed by a consortium, including Intel Corporation, to meet requirements similar to ZigBee, however, it is aimed exclusively at home automation and, furthermore, is not based on any recognized standard.

ZWave, like ZigBee, can use a self-adaptive mesh topology to achieve wide-range and reliable networking. Unfortunately it does not use any coordinator to achieve this and its bandwidth is lower capability than ZigBee. This results in higher power consumption and an increased chance of data packets collision among nodes.

Moreover a Z-Wave network is smaller than a ZigBee network which limits its potential applications and future expansion.

EnOcean do not use batteries. Their wireless sensors are powered by ‘energy harvesting’ such as temperature fluctuations, solar power, piezo-electricity, vibrations or movement.



	ZigBee	Wi-Fi	Bluetooth	Wireless USB	Wibree	Z-Wave	EnOcean
Standard	802.15.4	802.11x	802.15.1	USB	N/A	N/A	N/A
Application Focus	Monitoring & Control	Wireless LAN	Short range cable replacement	USB cable replacement	Low-power Bluetooth (eg. sensors)	Monitoring & Control	Monitoring & Control
Bandwidth	20 – 250 Kbps	54 Mbps	1 Mbps	110 – 480 Mbps	1 Mbps	40 Kbps	120 Kbps
Network Size	65536	32	7	N/A	*	232	*
Transmission Range	10 – 100m	50 – 100m	10m	10m	5 - 10m	30m	300m
Power Consumption	Very low	High	Medium	High	Low	Very Low	Extremely Low
Typical Applications	Home & Building automation, industrial controls, sensors	Wireless LAN connectivity	Wireless connectivity between devices (e.g. laptops & phones)	Computer peripherals	Low power connectivity, e.g. watches, sports sensors, toys	Home automation & sensor networks	Home & Building Automation, Sensors, Medical

Table 3.6 – Comparison of different wireless technologies

Like ZigBee, they form Hierarchical (tree) and mesh networks that can interface with IEEE 802.11x and ZigBee networks, however Unlike ZigBee and Z-Wave, it has been developed and patented by a single company limiting the market expansion.

Table 2.6 illustrate a brief comparison of the discussed wireless technologies.

4

WSN implementation aspects

In this chapter are presented many nontrivial problems and at least one of their solutions. The main reason to describe this problems is due to the need to use these solutions while implementing our WSN system.

4.1 Network formation and address assignment for a hierarchical (Tree) topology

It is important to note that, although the address assignment procedure is driven by MAC layer, with the ZigBee library provided with our nodes it is possible to force an assignment by an upper layer, having, in some circumstances, a better control on the network itself. In our system this kind assignment, according to the idea to easy the visualization of the network, it is used by default and create the short address (as explained later in this paragraph) with the last two byte of the device MAC address. This method is very easy to implement but is not completely safe (i.e. two nodes may have the last two bytes of MAC address with the same value).Moreover, when we designed our WSN system, this behavior did not make possible to implement the node backup system (described in the next chapter and named 'heartbeat' system) so we decided to use the address assignment described in this paragraph.

A wireless network is established by a join procedure, in our case a multi-hop network join procedure will be considered.

When a node *c* needs to join a network, a discovery procedure is started by the network layer. With support from the MAC layer scan procedure (see paragraph 3.3.1 and 3.5), it senses the adjacent routers, and when the upper layer has decided which network to join, the network layer selects a 'parent' node *p* from his neighborhood, and asks the MAC layer to start an association procedure.

If the association request from the MAC layer is satisfied, *p*'s network layer assigns *c* to a 16-bit short address and lets the MAC layer reply positively to the association request.

Node *c* will use the short address received for any further network communication.

The network, through the parent-child relationships established between nodes, has a tree shape with the PAN coordinator as the root, the ZigBee routers as internal nodes and end-devices as leaves.

The distributed algorithm for network address assignment is based on the tree structure of the network.

The ZigBee PAN coordinator fixes the maximum number of routers (*Rm*) and end-devices (*Dm*) that each router may have as direct children and also decides the maximum depth of the tree (*Lm*).

Thus to a newly joined router is assigned a range of consecutive addresses, 16-bit integers, on the basis of its position (depth) in the tree.

The first integer in the range is the router node address while the rest will be available for assignment to its children (both routers and end-devices).

The size A(d) of the range of addresses assigned to a router node at depth
d < Lm is defined by the following recurrence [BPC07]:

$$A(d) = \begin{cases} 1| + D_m + R_m & \text{If } d = L_m - 1 \\ 1 + D_m + R_m A(d+1) & \text{If } 0 \leq d < L_m - 1 \end{cases}$$

All nodes at depth L_m are assigned a single address as they are all end-node. The recursion is easily to be solved and it's used by each router to assign addresses to its children.

Assuming that a router at depth d receives the range of addresses [x,x + A(d)), It will have address x and it will assign range

$$\mathbf{[x + (n - 1)A(d + 1) + 1, x + n + A(d + 1)]}$$

to its n-th router child (1 ≤ n ≤ Rm) and address

$$\mathbf{x + R_m A(d + 1) + m}$$

to its m-th end-device child ($1 \leq m \leq D_m$).

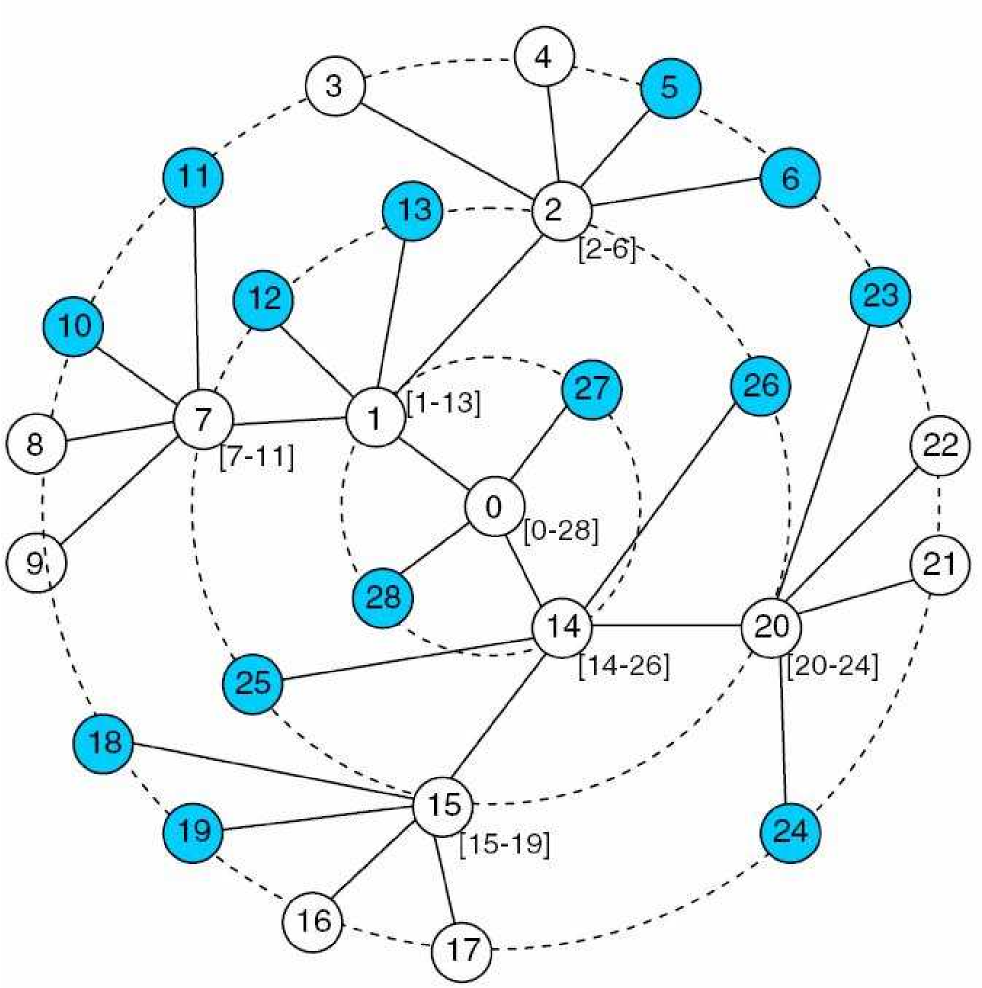


Figure 4.1 - Address allocations for Lm = 3, Dm = 2 and Rm = 2

Figure 4.1 show an example network with a maximum Level L_m = 3 and D_m = 2, R_m = 2 respectively, where all addresses have been assigned to end-devices (blue nodes) and routers (white nodes).

The address appears inside each represented node, while the assigned address ranges are displayed in brackets next to each router.

An alternative to this algorithm is proposed by [Sha08] and was used to develop our WSN system.

In this case the parameters affecting the address allocation are the following:

Lm. The network maximum depth (nwkMaxDepth).

Cm. The maximum number of children a parent can accept (nwkMaxChildren).

Rm. The maximum number of routing-capable children a parent can accept (nwkMaxRouters).

d The depth of a device in a network.

All the listed parameters are integer values and it will always be verified that Cm ≥ Rm.

Figure 3.4b shows an example of the application of this algorithm where Lm = 3, Cm = Rm = 2.

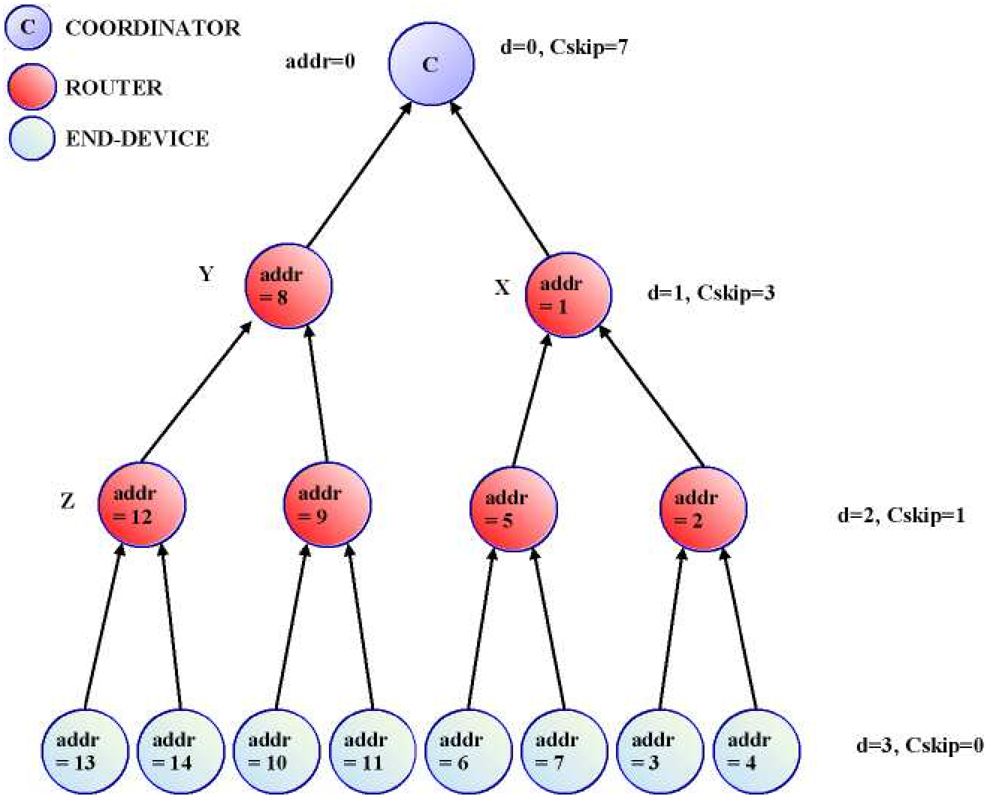


Figure 4.2 - Address allocations for Lm = 3, Cm = Rm = 2

The address allocation starts with assigning the zero address (addr = 0) to the WSN coordinator. To determine the address of the rest of the devices, a simple function (Cskip (d)) is introduced [PFL08]:

$$\text{Cskip (d)} = \begin{cases} 1 + C_m \times (L_m - d - 1) & \text{If } R_m = 1 \\ 1 + C_m \times \dfrac{(1 - R_m{}^{L_m - d - 1})}{1 - R_m} & \text{otherwise} \end{cases}$$

According to the parameters condition specified erlier Cskip(d) will always return an integer value.

In our example the value of Cskip(d) is calculated at each depth and the difference between the address of any two routing-capable devices is an integer multiple of the value of Cskip of their parent.

In the example, in Figure 4.2, the device X address is a single increment of the WSN coordinator address (addr = 1). The device Y address is the address of device X plus the value of Cskip of their parent (C skip = 7).

Therefore, the address of device Y is equal to 8 (addr = 8). The address of all the rest of the devices can be determined in the same way.

If the calculated Cskip value becomes zero it means that the device cannot accept any children therefore they will be simple end-devices.

In Figure 4.2, the Cskip value is equal to zero for all device s at level the depth level three.

The address of an end device that is not capable of routing is calculated differently.

Each end-device’s address is assigned using the following equation:

The n^{th} end device address=Parent address+Cskip(d)x R_m+n

For example, in Figure 3.4b , the end devices connected to device Z will have the following addresses:

First end device address =9+0·2+1=10

Second end device address=9+0·2+2=11

The Cskip(d) function can be very helpful when a device is expected to relay a message toward a destination on behalf of another device.

The relaying device needs to know whether the destination device is a descendant of the relaying device. If, as example, the relaying device is at depth d and its address is equal to A, a destination device with a destination address of D is a descendant of the relaying device if the following relationship is true:

$$A<D<A+Cskip(d-1)$$

For example, in Figure 3.4b, device Y is at depth one and has an address of 8 (A = 8). Then device Y receives a message that needs to be relayed toward the destination address of 11. Device Y uses the following to realize that the destination address is one of its own descendants:

$$8<11<8+7$$

Thus the destination is a descendant of a device, the next step is calculating the address of the next hop. If the destination is one of the device children, the address of the next hop will simply be equal to the destination address. If the destination is not a child but it is a descendant, the address of the next hop is calculated from the following equation:

$$\textbf{Address of the next hop= A +1+int} \left(\frac{D - A + 1}{\mathrm{Cskip(d)}}\right) \times \textbf{ Cskip(d)}$$

The function int calculate the integer part of any floating-point number.
In Figure 3.4b, when device Y needs to relay the message to destination address 11, the address of the next hop will be 9:

$$\textbf{Address of the next hop= 8 +1+int} \left(\frac{11 - 8 + 1}{3}\right) \times \textbf{ 3 = 9}$$

In a hierarchical topology, a device will relay a frame only if the frame was received along a valid path and this implies that one of the following conditions is satisfied [Sha08]:

The frame is received from one of the device children and the source device is a descendant of that child.
The frame is received from the device parent and the source device is not a descendant of the device.

Also the star topology can use this address assignement algorithm if we consider it a special tree network form where the only parent in the network is the ZigBee PAN coordinator. In a star network, all children are end-device at the depth of 1 and will communicate directly with the ZigBee coordinator.
The devices in a star topology cannot communicate directly with any device other than the ZigBee coordinator.
The address allocation method previously discussed is applicable to both ZigBee-2006 and ZigBee PRO 2007.

4.1.1 Routing in ZigBee tree topology

The network routing algorithm is strictly topology's dependent. In a tree topology routing can only happen along the parent-child links established as a result of join operations (this is called ‘‘tree-based routing’’).
The routers maintain only their own address and the address information about their children and parent. When the way addresses are assigned, a

router can easily determine whether the forwarded message destination belongs to a tree rooted at one of its children (router or end-device). In this case it routes the packet to the appropriate child; otherwise it routes the packet to its parent.

This routing algorithm is very simple to implement, and allows routers to operate in a beacon-enabled network although is not necessarily the most energy-efficient.

All ZigBee routers and coordinators send beacons to communicate via a slotted CSMA-CA protocol (as described in paragraph 2.4.1) and sleep in the inactive portion of their superframe (see par. 2.6).

The trick, of course, is to have short active periods compared to the beacon interval and having the neighbouring routers start their superframe suitably respect to one another to avoid overlapping frames.

Communication from a child to a parent happens only in the CAP (see par. 2.4.1) of the parent while communication from a parent to a child is indirect. While a node drives communication with its children according to its superframe it has to synchronize with the parent’s beacon to exchange data with it.

4.2 Routing algorithms for a mesh topology

The mesh routing algorithms information was used to balance the routing table, used do decide the next destination of a message, that requires our few memory resource, with the network capabilities (i.e. number of discovered routes). Our WSN does not have many nodes and a table with twenty entry can cover the entire network, without exhausting the device resources. Of course, if we plan to add more nodes, depending from the new numbers, the decision may be different and a new compromise between table size and resource saving can be chosen (but is not our subject of study).

In a mesh topology, unlike to the tree topology, there are no hierarchical relationships. Any device in a mesh topology is allowed to attempt to contact any other device. The message can be sent directly to the destination node or by taking advantage of routing-capable devices to relay the message.

In mesh topology, the route from the source node to the destination is created on demand and can be modified according to the environment changes. The capability of a mesh network to create and modify routes dynamically greatly increases the reliability of the wireless connections.

If, for any reason, the source device cannot communicate with the destination device, by using a previously established route, the routing-capable devices in the network cooperate to find an alternative path.

Ad hoc networks use commonly two routing algorithms as a basis for the development of a mesh network.

Those routing algorithms are named respectively dynamic source routing and on-demand distant vector.

The mesh network topology is more complex and beaconing is not allowed but, as noted before, is more fault tolerant and resilient.

Routers maintain a routing table (RT) and perform a route discovery algorithm to construct or update these data entry structures on all the path nodes.

The routing table entry is described in Table 4.1.

Field Name	Description
Destination Address	16-bit network address of the destination
Next-hop Address	16-bit network address of next hop towards destination
Entry Status	One of Active, Discovery or Inactive

Table 4.1 – RT's record structure

In figure 4.3 is depicted a simplified version of the routing algorithm used to send a packet.

As can be noted, when a direct routing is not possible, the routing table is consulted for the next hop to the destination.

If no entry addresses the given destination, the node attempts to start the route discovery procedure and in case there aren't sufficient resources available it falls back to the tree-based routing.

4.2.1 Dynamic source routing

Dynamic source routing is one of several protocols being analyzed by the IETF for use thanks to ad hoc wireless networks.

This routing protocol is based upon the concept of source routing and it was implemented to enable each node to be mobile.

A source routing represents an Internet Protocol (IP) option that, when enabled, allows the originator of a packet to specify the complete path it will take to its destination as well as the path responses take when the destination responds to the originator [Hel05].

Source routing is defined in the RFC791 standard and is mainly used for diagnostic testing of a specific route or when the default route connection is not optimal.

Dynamic source routing is very similar to IP source routing. A route request is used under dynamic source routing to determine the path from the source to the destination.

The destination issues a route reply, providing the reverse path. The route between source and destination does not need to be a perfect reversed image of the path between destination and source, although some protocols require bidirectional connections.

The IEEE 802.11 standard is one of such protocols and enables a destination node on a wireless LAN using dynamic source routing to reverse the route to itself to determine the route to the source node. Each node, in a dynamic source routing environment, examines every packet it receives. This operating method is referred to as promiscuous mode.

The node by examining the addresses in each packet learns where other devices are located. Due to this, nodes do not need to transmit periodic routing advertisements, such as Routing Information Protocol (RIP) transmissions used to inform other nodes of the state of the network.

4.2.2 On-demand distant vector

The second ad hoc routing algorithm is the On-demand Distance Vector (ODV) algorithm. Each router, under this routing algorithm, informs its neighbors about its network view in a subnets' form of directly connected to the device itself.

The neighbors uses this information to compute their distances to all other subnets.

The on-demand distance vector algorithm uses periodic messages to track the state of the link between two nodes.

4.2.3 Zigbee Route discovery

The Route discovery algorithm in ZigBee is based on the well-known Ad-hoc On Demand Distance Vector routing algorithm(AODV) briefly descripted in the previos paragraph.

Route discovery is a process required to establish routing table entries in the nodes along the path between two nodes wishing to communicate.

It selects the path through which the messages will be relayed to their destination's device.

The WSN coordinator and all routers are responsible for discovering and maintaining the routes in a network. An end device cannot perform route discovery.

The length (L) of a path is defined as the number of devices in the path. As an example, Figure 3.5 shows two paths with the lengths of five (L = 5) and seven (L = 7). The connection between two consecutive devices is called a link . The links are numbered l_1 to l_4 in Figure 3.5.

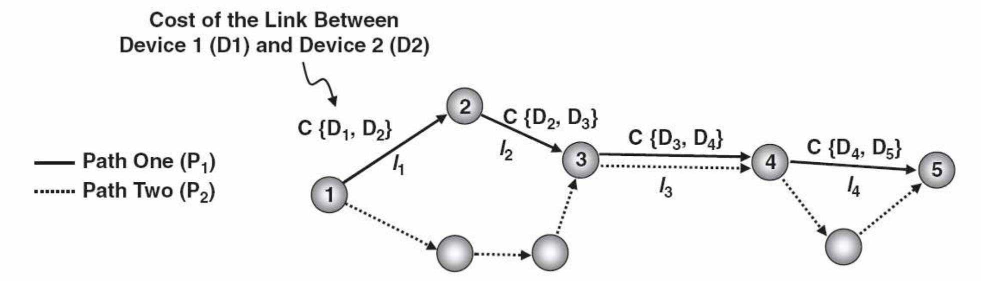


Figure 4.3 – Path cost analysis

Parameters such as link's quality, number of hops can be used to decide on the optimal path.

To simplify the whole process each link is associated with a link cost . The probability of successful packet delivery on each link will determine the link cost. Thus a lower probability of successful packet delivery will have a higher link cost. The link cost is shown as C { [D_i ,D_{i+1}] } in Figure 3.5 .

There are various ways to determine link cost. The ZigBee standard uses the following equation [Azz08]:

$$\textbf{C\{l\} The lesser of 7 and round} \left(\frac{1}{P_i^{\,4}} \right)$$

C{l} is the cost of link l. The probability of successful packet delivery in link l is shown by P_l. The round function rounds the number to the nearest integer value. The cost is always an integer between 0 and 7. For example, if P_l is 80%, the cost of the link will be the integer 2:

$$\textbf{C\{l\} The lesser of 7 and round} \left(\frac{1}{0{,}8^4} \right) \mathbf{=2}$$

The probability of successful packet delivery (P_l) can be estimated using various methods, and the ZigBee standard allows the implementers to select any method they find most suitable for their application.

However, the initial estimate for the probability of successful packet delivery must be based on average LQI.

The LQI is recorded for each received packet, indicating the signal energy. Usually the chance of successful reception of a packet increases as the LQI is increased.

A method to calculate the link cost is to use a lookup table to map different levels of LQI directly to the link cost levels of 0 to 7.

This table is usually created according to the average results of several experiments.

To compare different paths, each path has its own path cost. The total path cost (C{P}) is simply the summation of all the costs of the links that form the path:

$$\mathbf{C\{\mathit{P}\}} = \sum_{i=1}^{L-1} C\{[D_i, D_{i+1}]\} = \sum_{i=1}^{L-1} C\{l_i\}$$

Field Name	**Size**	**Description**
Destination address	2 bytes	The route will lead to this destination address
Status	3 bits	The route status can be one of the following: ACTIVE, DISCOVERY_UNDERWAY, DISCOVERY_FAILD, INACTIVE, VALIDATION_UNDERWAY
Many-to-one	1 bit	If the destination has issued a many-to-one route request,this field is set to one
Route record required	1 bit	If this flag is set, the route taken by the packet will be recorded and delivered to the destination device
Group ID flag	1 bit	This flag is set if the destination address is a group ID
Next-hop address	2 bytes	This is the 16-bit network address of the next hop in this route

Table 4.2 - Routing Table (RT)

The route with the lowest path cost will have the best chance rate of successfully deliver packets.

The WSN coordinator and routers create and maintain routing tables (see Table 4.2).

The routing table is used to determine the next hop when routing a message to a particular destination. The status field determines the status of a route. The routing table capacity property means that the device is capable of using its routing table to establish a route to a specific destination address.

Field Name	**Size**	**Description**
RREQID	1 byte	Unique ID (sequence number) given to every RREQ message being broadcasted
Source Address	2 bytes	Network address (16-bit) of the initiator of the route request
Sender Address	2 bytes	This is the 16-bit network address of the sender device. The sender device is the device that has sent the route request on behalf of the source device to the current device. This address will be used to send the route reply command back to the source device. If the same route request is received from multiple senders, the address of the sender with the lowest overall path cost will be kept here.
Forward Cost	1 byte	The accumulated path cost from the RREQ originator to the current device. This field is updated when the route request command is being sent toward the destination devic
Residual Cost	1 byte	The accumulated path cost from the current device to the RREQ destination This field is updated when the route reply command is being sent back to the source device
Expiration time	2 bytes	The content of the route discovery table expires after a certain period. The initial value of this field is equal to nwkcRouteDiscoveryTime .

Table 4.3 - Content of the Route Discovery Table (RDT)

Another table related to routing, which is used during the discovery of new routes is the route discovery table. Table 4.3 illustrates the discovery entry contents structure.

The route discovery table contains the path costs, the address of the device that requested the route (called source device), and the address of the last device that relayed the request to the current device. The latter will be used to send the result of the route discovery back to the route request originator (source device).

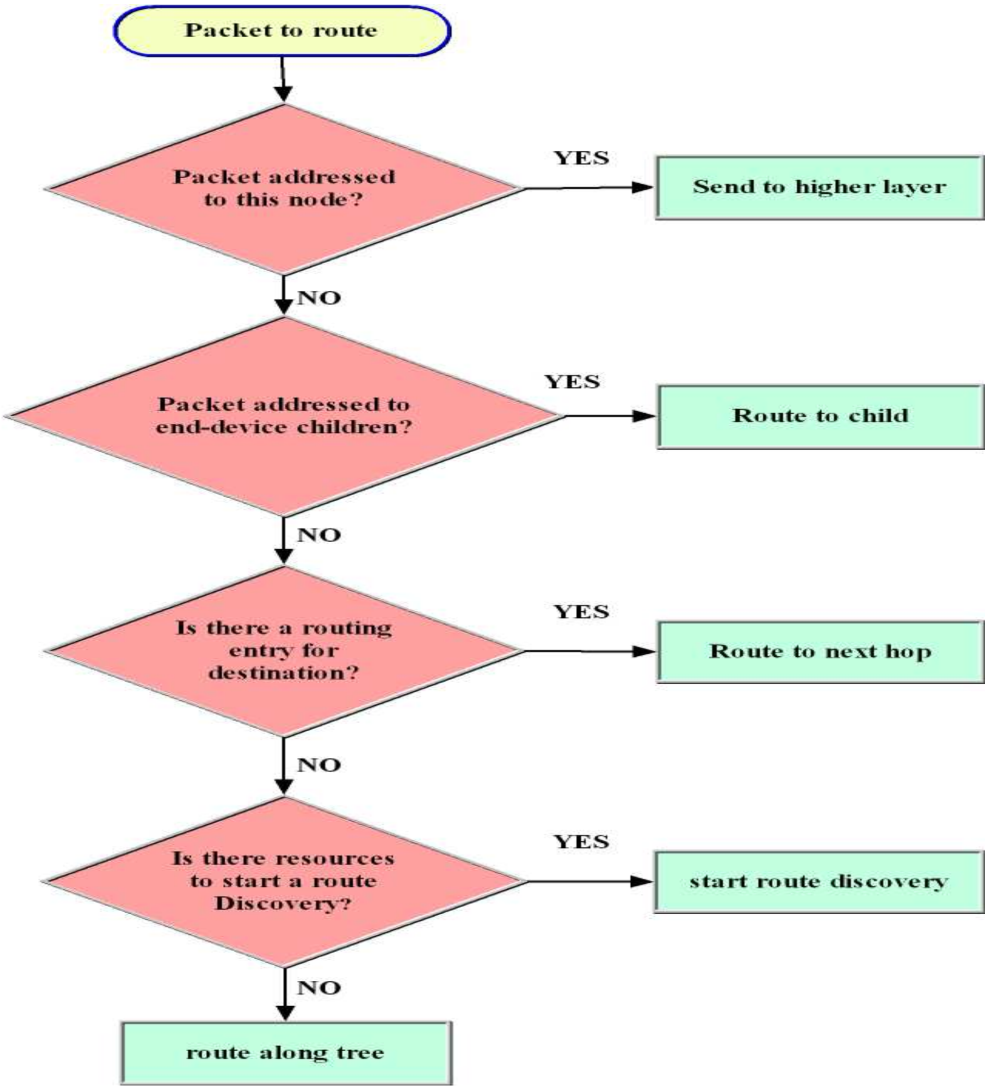

Packet to route
Packet addressed to this node?
YES
Send to higher layer
NO
Packet addressed to end-device children?
YES
Route to child
NO
Is there a routing entry for destination?
YES
Route to next hop
NO
Is there resources to start a route Discovery?
YES
start route discovery
NO
route along tree

Figure 4.4 - Routing protocol flow diagram

All routers and the coordinator maintain a Route Discovery Table (RDT) to implement route discovery.

The content of the route discovery table, in contrast with the routing table, is temporary and expires after *nwkcRouteDiscoveryTime* milliseconds.

In a ZigBee network a node also maintains a neighbor table , which contains information about the devices in its transmission range (Table 4.4). This table is updated every time the device receives a packet from one of its neighbors. This table is useful when the node needs to find a nearby router or rejoin the network.

The device also uses the neighbor table when it seeks a new parent. Table 4.4 includes all required fields and some of the most important optional fields.

Field Name	**Description**
Extended address	64-bit IEEE 802.15.4 address
Network address	16-bit network address
Device type	ZigBee coordinator, router, or end device
RxOnWhenIdle	If the device keeps its receiver ON during idle mode, this field is set to TRUE
Relationship	This field determines the relationship of the neighbor to the device as parent, child, sibling, previous child, or none of the above
Transmit failure	A high value in this field indicates that many of the previous transmission attempts resulted in failure
LQI	The estimated link quality
Incoming beacon timestamp	The time that the last beacon was received (optional field)
Potential parent	This field determines whether this neighbor is a potential parent (optional field)

Table 4.4 - The Neighbor Table

4.2.4 Route discovery

The Application (APL) layer can use the NLME-ROUTE-DISCOVERY primitive to request that the Network (NWK) layer discover routes for unicast, multicast, or many-to-one communication.

If the discovery request contains the address of an individual node as the destination address, the NWK layer will perform a unicast route discovery. An unicast route always starts from a single originator address and ends at a single destination address. Conversely a multicast route discovery will be initiated if the destination address is a 16-bit group ID of a multicast group.

If the APL layer does not provide a destination address, the NWK layer will consider that the APL layer has requested a many-to-one route discovery.

The many-to-one routes will promote the device that requested the route discovery as the sink device.

Only the WSN coordinator and routers are capable of perform a route discovery request. Moreover, the ZigBee standard does not allow a broadcasting's route discovery. Thus if the APL layer issues the NLME-ROUTE-DISCOVERY request primitive to the NWK layer with the destination address equal to the broadcast address (0xffff), the primitive will be treated as an invalid request and discard it.

When a node needs a route to an un-localized destination, it broadcasts a route request (RREQ) message that propagates through the entire network until it reaches the destination.

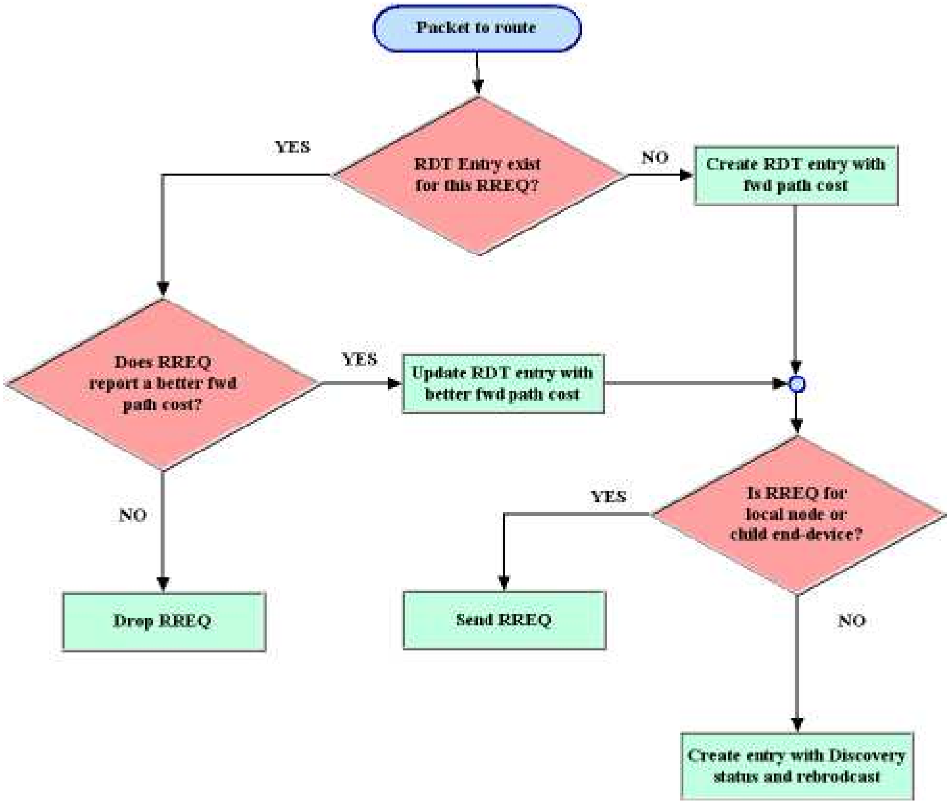

Packet to route
RDT Entry exist for this RREQ?
YES
NO
Create RDT entry with fwd path cost
Does RREQ report a better fwd path cost?
YES
Update RDT entry with better fwd path cost
NO
Drop RREQ
Is RREQ for local node or child end-device?
YES
Send RREQ
NO
Create entry with Discovery status and rebrodcast

Figure 4.5 - The RREQ message processing algorithm

As it travels in the network, a RREQ message accumulates, in the Forward Cost field, a value that is the sum of the costs of all the links it traversed.

The cost of a link can be dynamically calculated based on a link quality estimation provided by the IEEE 802.15.4 interface or simply set to a constant value.

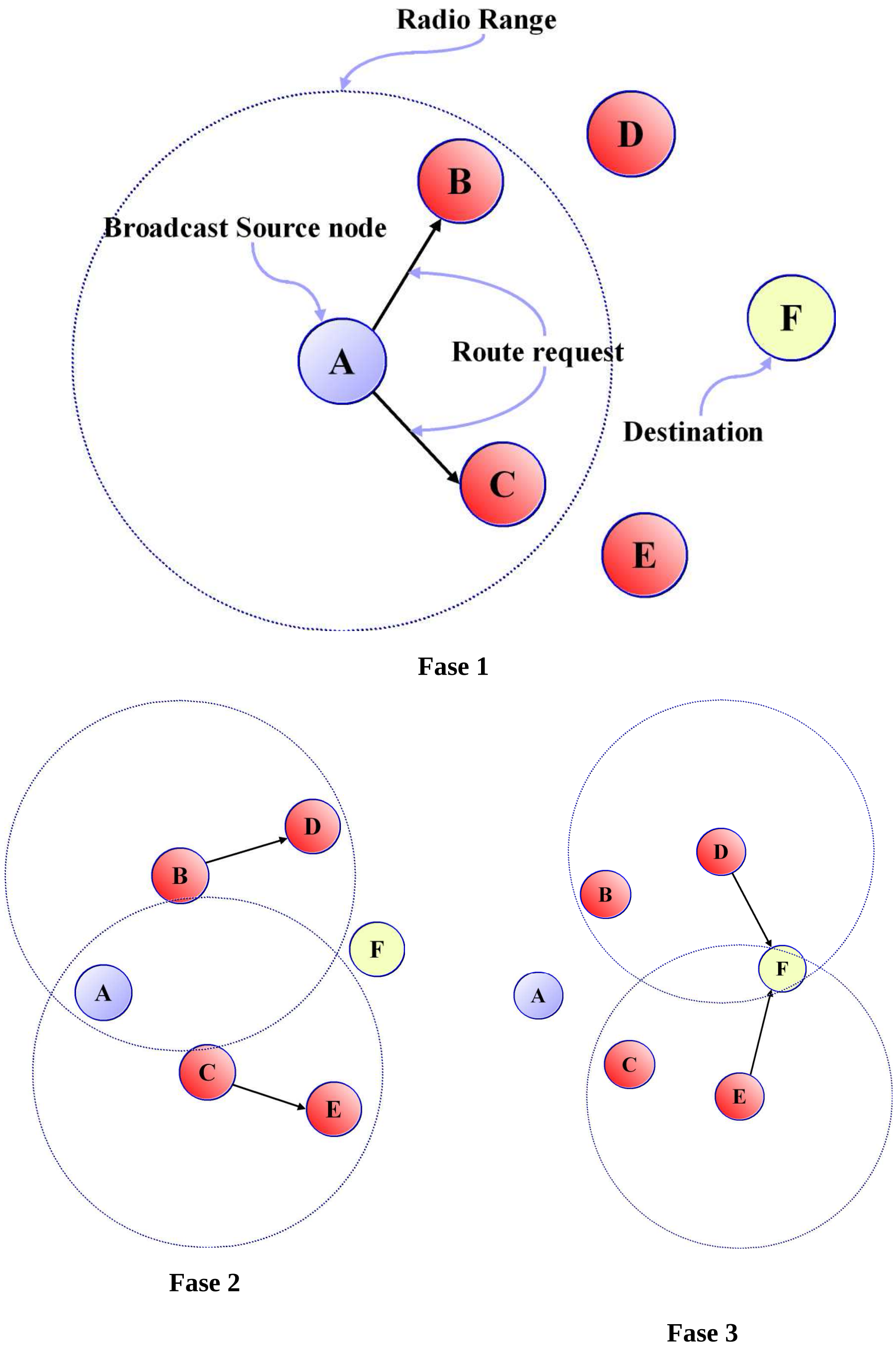
In figure 4.5 is depicted the RREQ message processing flow diagram while in algorithm 4.1 is shown the pseudo code for the function implementation.

```
// S is the source node; D is the destination node
// RT = Routing Table
S wants to communicate with D
if RT of S contains a route to D
  S establishes communication with D
else
  S creates a RREQ packet and broadcasts it to its neighbors
  // RREQ contains the destination Address(DestAddr),
  // Sequence Number (Seq) and Broadcast ID (BID)

  for all nodes N receiving RREQ
    if (RREQ was previously processed)
      discard duplicate RREQ
    end if
    if (N is D)
      send back a RREP packet to the node sending the RREQ
    else if (N has a route to D with SeqId >= RREQ.Seq)
      send back a RREP packet
    else
      record the node from which RREQ was received
        broadcast RREQ
    end if
  end for

  while (node N receives RREP) and (N != S)
    forward RREP on the reverse path
    store information about the node sending RREP in the RT
  end while

  S receives RREP
  S updates its RT based on the node sending the RREP
  S establishes communication with D
end if
```

Algorithm 4.1 - AODV Routing Protocol

Each RREQ message carries a RREQ ID which the source node increments by 1 every time it sends a new RREQ message thus the RREQ ID together with the source address together can be used as a unique reference for a route discovery process.

The RREQ reception event starts up a search within the RDT for an entry matching the route discovery. If no match is found, a new RDT entry is created for the discovery process and a route request timer is started and it will be removed upon the expiration event occur.



Fase 1

Fase 2

Fase 3

Figure 4.6 - Unicast Route Discovery with Device A as the Source and Device F as the Destination

Otherwise if an entry is found in the RDT, the node compares the path cost for the corresponding value in the RDT entry and the RREQ message. If the former is higher it drops the RREQ message, otherwise it updates the RDT entry.

If the node, finally, is not the route discovery destination, it allocates an RT entry for the destination, with Discovery status, and rebroadcasts the RREQ after updating its path forward cost field.

If the node, instead, is the final destination, it replies to the originator with a route reply (RREP) message that travels back along the path.

In figure 4.5 is depicted the block diagram illustrating the explained RREQ processing [Bou08].

Figure 4.6 shows an example of unicast route discovery. In this scenario, device A intends to find a route to device F. Device A starts the route discovery by broadcasting a route request command. The route request command frame (see paragraph 3.5.1 for the command frame structure) contains the route request identifier, the destination address, and a path-cost field as previously explained.

The broadcast command is received by all the devices that are in device A radio range and are listening to the same channel. In Figure 4.6 , device B and device C receive the route request command.

Device A will wait for passive acknowledgment, and if the broadcast was not successful device A will retry the broadcast for *nwkcInitialRREQRetries* times after the initial broadcast. These retries are separated by *nwkcRREQRetryInterval* milliseconds.

If a ZigBee end device has received the route request command it will simply ignore this command because it does not have routing capability.

Figure 4.6 shows only the routing capable devices located between device A and device F, either ZigBee coordinators or ZigBee routers. Device B is a ZigBee router, and if device B has routing capacity, meaning a non-full routing table, it will perform all the operation required such as adding the path cost from device A to device B to the path-cost field of the routing request command and broadcasts the route request command.

The consecutive broadcasting is repeated until the route request command is received by the intended destination (node F).

Device F will use the total accumulated path cost of each received route request command to select the optimum path from device A to device F. Device F will choose either device D or device E as its next hop for transmitting the route reply command (RREP) back to device A.

The RREP message is addressed to the route discovery source and has a residual cost value field that each node increments as it forwards the message.

When a node receipt a route reply message, it retrieves the RDT and RT entries for the associated route discovery. The RREQ originator node upon the receipt of the RREP sets the RT entry, if this is the first it received, to Active and records the residual cost and next hop in the RDT entry.

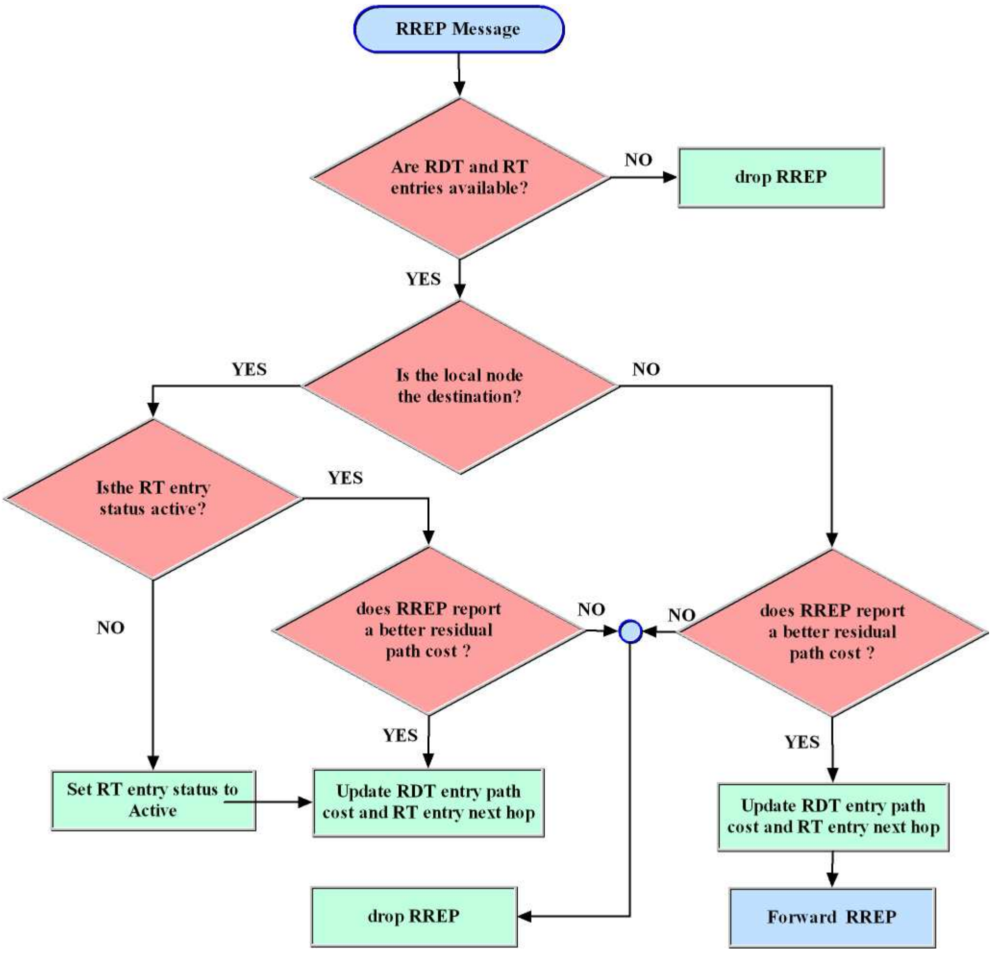

RREP Message
Are RDT and RT entries available?
NO
drop RREP
YES
Is the local node the destination?
YES
NO
Isthe RT entry status active?
YES
NO
does RREP report a better residual path cost ?
NO
NO
does RREP report a better residual path cost ?
YES
YES
Set RT entry status to Active
Update RDT entry path cost and RT entry next hop
Update RDT entry path cost and RT entry next hop
drop RREP
Forward RREP

Figure 4.7 - The RREP message processing algorithm

In all other cases it compares the residual cost from the RDT entry with the one from the RREP. If the former value is higher the node discards the RREP message; otherwise it updates the RDT entry (residual cost) and the RT entry (next hop).

A node that is not the RREP source, after the update/discard operation, must also forward the RREP towards the originator.

As to be underlined that intermediate nodes never change the RT entry status to Active as a result of receiving a RREP message.

They will only change the entry status upon reception and routing of a data message for the given destination.

4.2.5 Route maintenance and repair

Meanwhile a discovered route is used to relay the messages, there can be incidents in which the route itself is not capable of relaying a message anymore to the destination.

The reason can be inside the network (e.g. a router has been removed or turned off) or from the surrounding environment (e.g. an object or a signal is blocking the wireless connection between two nodes).

Considering the great effort required to create or repair a route, it is not recommended to start a repair procedure as soon as a route fails. Instead, it is better to keep a counter for the number of times that an outgoing frame has failed due to a link failure.

A route repair procedure will start when this counter exceeds the *nwkcRepairThreshold* value.

If it's possible (it depend on the node capabilities) is a good choice to record the time that the link has failed. This will help distinguish between permanent and temporary link failures.

The developer will decide on the best method to start the route repair based on the scenario.

If the route error occurred in a many-to-one topology, the device that has found the link failure will send a route error command message to a random neighbor.

All neighbors are expected to have a routing table to the sink (destination) device. The neighbor will then forward the route error command frame to the sink device.

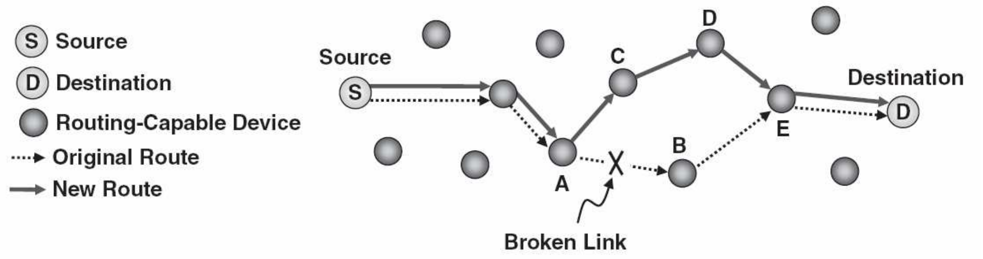


Figure 4.8 - Route Repair in a Mesh Network

In Figure 4.8 is depicted an example of mesh network route repair procedure. The link between node A and node B has failed and a route repair is requested.

The procedure for route repair is similar to route discovery except that device A, instead of the original source device, will start the route discovery. Device A will use its own address as the source device when broadcasting a route request command frame to find the new route to the destination device.

Route repair and route discovery use the same route request command thus to distinguish a route repair from a route discovery a single bit subfield must be set (to one) for route repair request command (the frame is shown in figure 3.13).

In Figure 4.8 a new route has been established between the originator and the destination address.

The new route may share, along the way, some of the devices with the original route.

If device A cannot establish a new route to the destination (it failed to repair) it unicasts a route error command back to the originator.

The source device in this case will start a new route discovery to establish routes to the destination address.

4.3 The NWK layer management service

The NWK layer was modified by the author to implement the fault tolerance such as the heartbeat system described in the next chapter and to improve the security of the system in consideration of the several flaws found in the ZigBee stack.

The NWK layer main responsibilities, as briefly described in paragraph 3.6.1, are network formation, joining and leaving a network, route discovery and maintenance.

The NWK layer routing and route discovery were discussed earlier in the previous paragraph. The rest of NWK layer capabilities are reviewed in this paragraph and its subsections.

4.3.1 Network discovery

The network discovery procedure is used to discover all the networks currently operating in the device environment. The device discovery request is sent to the NWK layer by the APL layer.

The NWK layer uses the MAC layer channel scanning to discover the existence of other networks.

The active scan is the preferred scan method if the device is capable of performing an active scan. Otherwise, the device will perform a passive scan.

The network discovery procedure delivers the list of discovered networks, and their PAN identifiers, the currently used channels, and the version of the ZigBee protocol used to the APL layer.

Information includes also the value of beacon order, super-frame order of the networks, and their ZigBee stack profile identifiers.

The network discovery procedure will verify if there is at least one router in any discovered network that currently allows joining.

4.3.2 Network formation

Upon the receipt of any request from the APL layer the NWK layer can establish the device as the ZigBee coordinator.

The device must be an FFD (see par. 3.3.1) to act as a ZigBee coordinator.

The first step of network formation is performing an ED scan. The ED scan is an energy level detector for each channel and is performed using the PHY energy detection service (refer to paragraph 2.4 for more information). This ED scan is optional for RFDs. This scan is followed by an active scan on a selected number of channels using the MAC services.

The scan request is issued by the Network Layer Management Entity (NLME) to the MAC Layer Management Entity (MLME) see fig. 3.21 for more information about the ZigBee Architecture.

Based on the scan results, the NWK layer choose a frequency channel and a unique PAN identifier. The first channel with the lowest number of existing networks is considered a proper frequency channel to be used in the new network.

The NWK layer of the ZigBee PAN coordinator assign 0x0000 as its MAC short address, which is the same as the network address and then it will is configure the super frame using the MAC services.

4.3.3 Establishing the device as a ZigBee router

As described before a router is responsible for routing data frames, route discovery, and route repair. The router can establish its super frame and accept the requests from other devices to join the network. The request to establish the device as a router is performed by APL layer sending to the NWK layer a *NLME-START-ROUTER.request*.

Considering that a router can form its super frame, this primitive includes all the super frame parameters such as Beacon Order, Super frame Order , and BatteryLifeExtention (BLE). The NWK layer requests the MAC layer to create or update the super frame configurations

4.3.4 Joining and leaving a network

If the MAC attribute *macAssociationPermit* , in any device, is set to TRUE, the device will accept association requests.

The NWK layer of a ZigBee coordinator or router can allow other devices to join its network via a MLME request to set the value of *macAssociationPermit* to TRUE for a limited (and fixed) period of time.

This period is known as ‘permit duration’ .

The APL layer can invoke the *NLME-JOIN.request* primitive to request the NWK layer to join the device to a network as either as a router or an end device.

The MAC layer of the child delivers the list of discovered networks to the NWK layer. The child then picks a suitable parent. A parent is considered suitable if it allows association and the link cost between the parent and the child is a value less than 3 (see Cost formulae in par. 4.2.3).

If there is more than one suitable parent then will be selected the parent in the lowest depth from the ZigBee coordinator.

Selected the parent, the NWK layer of the child initiates the association procedure using the *MLME-ASSOCIATE.request* primitive.

When the parent device receives the association request, it will determine whether the device is already in the parent network as a child by looking up its neighbor table. If this node is not found in the neighbor table, the child will receive a unique network address.

Each parent has only a fixed number of addresses available to allocate to its children. If the request to join is granted, the parent will update its neighbor table adding the new device as its own child.

The NWK rejoin request command will be used, instead, if the device was previously associated with this parent. A child can always rejoin its parent even if the parent currently does not accept any new child.

An alternative way to join a network is the direct join. The direct join is used when the parent is already preconfigured with the 64-bit addresses of its children. In this case, the child does not attempt to find a suitable parent, because its parent is already selected for it [IEE06].

The parent will initiate the join procedure by searching its neighbor table to identify whether the 64-bit address of the child is already listed in the table. If a match exists in the neighbor table, no further action is required from the parent. If the address is not found in the neighbor table and the table itself is not full, then the parent will create an entry in the table.

In the direct join the parent does not contact the child therefore the child is responsible to start an orphan procedure to complete the child/parent relationship.

Removing a child from the network can be initiated indifferently by the child itself or its parent. The MAC layer disassociation function is used to remove a device from the network. When a node leaves a network, all its children can be removed from the network as well.

These removed children can join new parents in the network or join another network, depending on the implemented application and scenario.

If the node that plans to remove itself from the network is the PAN coordinator or a router, the NWK layer leave command frame is broadcast to the entire network by selecting the address of 0xffff as destination.

The reason for broadcasting the leave command is to let all the devices that count on this specific router or coordinator know that they need to update their routes or find new parents if necessary.

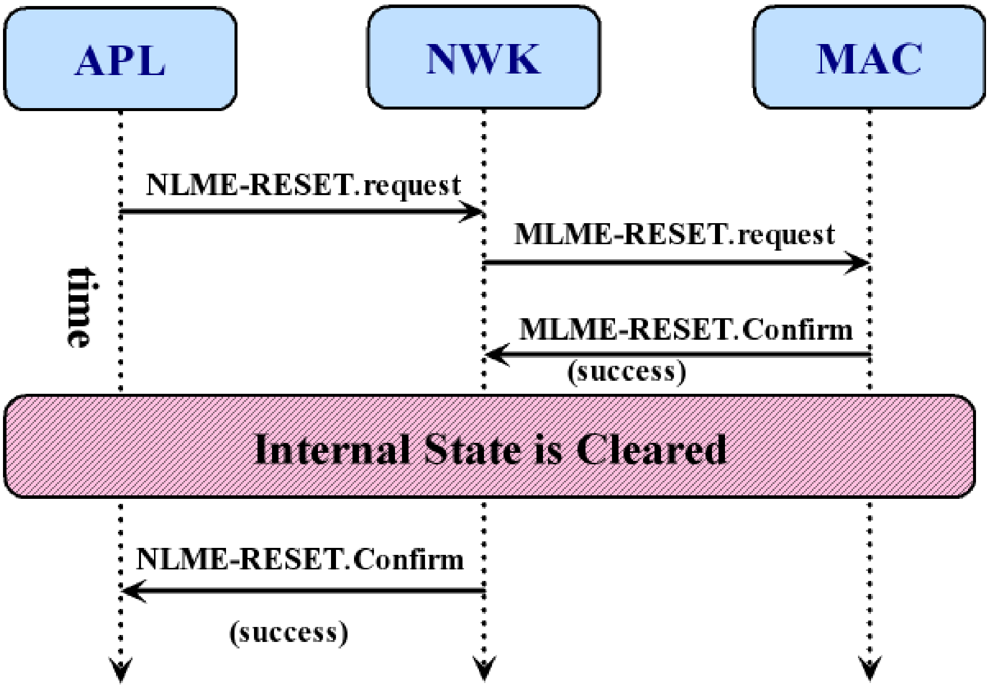


Figure 4.9 - Network Layer Reset Sequence

Conversely a ZigBee end device send the leave command only to its parent. In both cases, the APL layer invoke *NLME-LEAVE.request* primitive to request the NWK layer initiate the removal procedure.

When the parent decides to remove a child, it unicasts the leave-request command to the child. After the child is successfully removed the parent updates its neighbor table accordingly.

The address of the removed child can be reused only if the APL layer allows the address reuse in the *NLME-LEAVE.request* primitive sent to the NWK layer for the removal of this child. If the removed child is a router, the child will broadcast a leave command by selecting the destination address equal to 0xffff.

4.3.5 Resetting the NWK layer

The NWK layer can perform reset operation (Figure 4.9) upon request of the its higher layer. The NWK layer first resets the MAC layer and after receiving the MAC reset confirmation, the NWK layer clears all Network

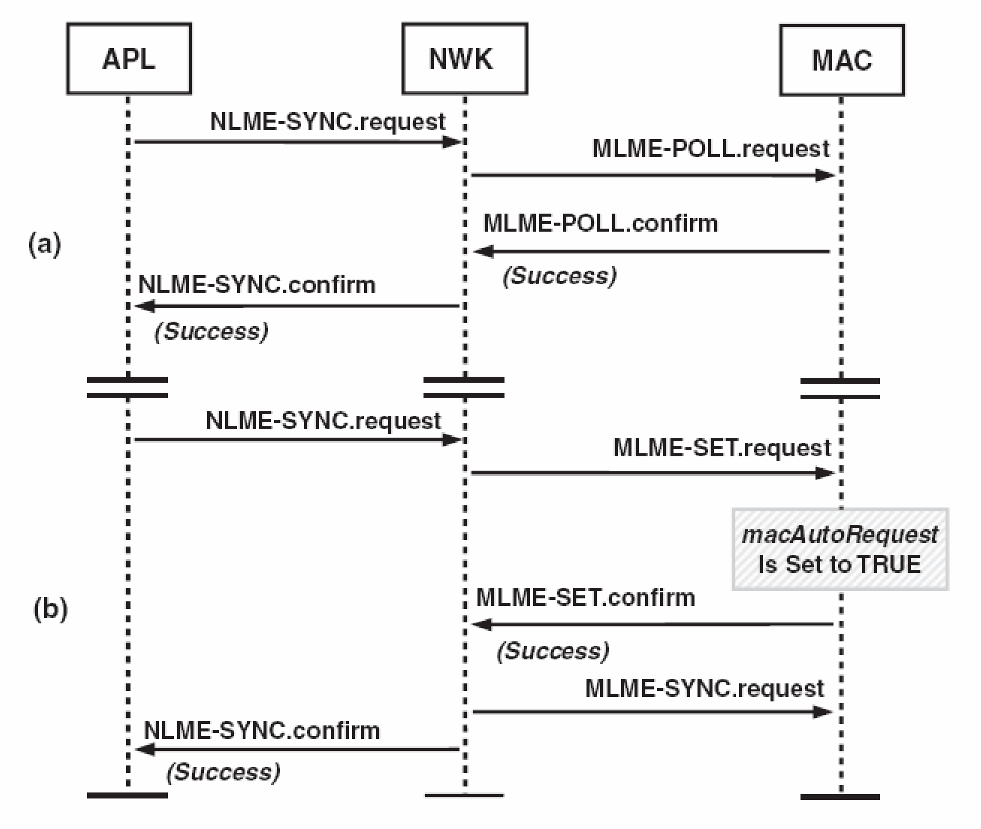


Figure 4.10 - Synchronization in (a) A Non beacon-enabled Network and (b) A Beacon-enabled Network

Layer Information Base (NIB) attributes, routing tables, and route discovery tables to their default values. The reset request is given by the APL layer in the form of *NLME-RESET.request*. The NWK layer will confirm the result of the reset operation by the *NLME-RESET.confirm* function to the APL layer. A device usually performs the NWK layer reset after the initial power up, before a new join attempt and after leaving a network.

4.3.6 Synchronization

A WSN node can use a synchronization procedure to synchronize or extract pending data from a ZigBee coordinator or router. There are two synchronization scenarios: beacon enabled and non-beacon enabled.

Figure 4.10 illustrates the sequence diagram for both cases.

When the value of *macAutoRequest* is set to TRUE the MAC generate and send a data request command automatically.

The APL layer uses the *NLME-SYNC.request* to ask the NWK layer to initiate the synchronization and data request process. The result of synchronization is delivered to the APL layer by NLME-SYNC.confirm.

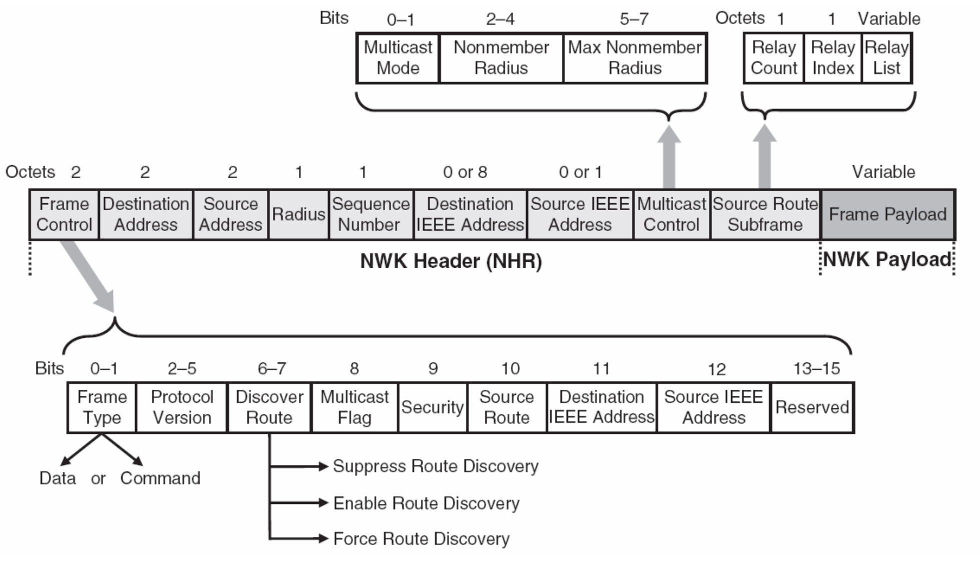


Figure 4.11 - General Network Frame Format

4.3.7 The NWK layer frame formats

The general NWK frame is illustrated in Figure 4.11. It starts with the frame control field. The frame type determines if this is a NWK data frame or a NWK command frame.

Since the ZigBee standard evolves a ZigBee protocol version is used in each device and is stored in *nwkcProtocolVersion*. The value of *nwkcProtocolVersion* is always copied into the protocol version subfield of a NWK frame.

The route discover subfield determines the routing option for this single frame. If the discover route subfield is set to suppress or enable and a route is already established to the destination, the frame will be sent to the next hop. However if there is no route established to the destination device and the discover route is set to suppress, the device will not start a new route discovery. In this case the frame will be discarded or buffered until the route becomes available. If the discover route subfield is set to enable, a route discovery will be initiated if there is no route to the destination.

Finally, if the route discovery value is set to force route discovery, a route discovery will be initiated for this frame transmission, even if there is a existing route established to the destination.

In ZigBee-Pro, the force route discovery option is removed from the discover route sub-field.

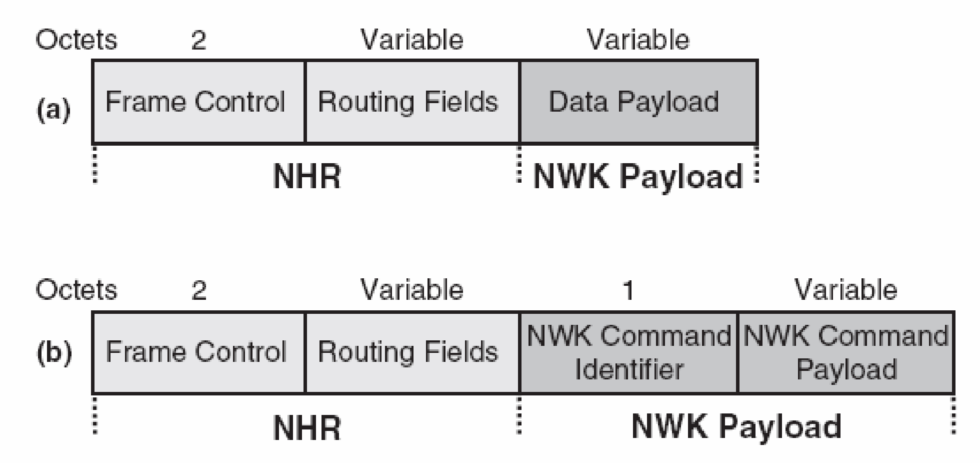


Figure 4.12 - The NWK Layer (a) Data Frame Format and (b) Command Frame Format

The multicast flag subfield decides whether the frame will be sent using multicast (must be set to one). The security subfield is set to one if the NWK layer security is enabled. The source route subfield in the frame control is set to one if the source route sub frame field is included in the frame. Source routing is a technique in which the sender of a packet specify the route that a packet should take through the network. The source route subframe contains the list of 16-bit short addresses of the devices that will be used to relay the message. The relay index is set to zero at the originator device and is incremented every time the frame is relayed. The relay count represents the number of times the frame is relayed.

The NWK layer can include the 64-bit IEEE address in the NWK layer frames if the IEEE address subfields are set to one. The 16-bit network address of both the source and destination are always included in the frame. The radius value will determine the maximum number of hops of the frame. If the radius parameter is not provided, the radius field is set to twice the value of the *nwkMaxDepth* attribute.

The sequence number allows to keep track of the sequences transmitted by a node and its value is incremented every time a new frame is transmitted.

The multicast control field exists only if the frame is multicast. The multicast mode value determines whether the frame is being sent by the device in member or non member mode (respectively multicast mode set to 01 or to 00). The non member radius subfield limits to a fixed number of times a multicast frame which is rebroadcast by nonmember nodes.

Command Frame Identifier	**Command**
00000001	Route request
00000002	Route reply
00000003	Route error (network status)
00000004	Leave
00000005	Route record
00000006	Rejoin request
00000007	Rejoin response
00000008	Link status (ZigBee-Pro)
00000009	Network report (ZigBee-Pro)
0000000A	Network update (ZigBee-Pro)

Table 4.5 - NWK Commands

The nonmember radius value is decremented every time the frame is rebroadcast by a non-member device and when it becomes zero, the frame is no longer rebroadcast by nonmember devices.

However, if the content of the non-member radius is set to 0x07, there is no limit on the number of times that the frame can be broadcasted by non-member nodes. Every time a member broadcasts the frame, it will copy the content of the max non-member subfield into the non-member radius subfield.

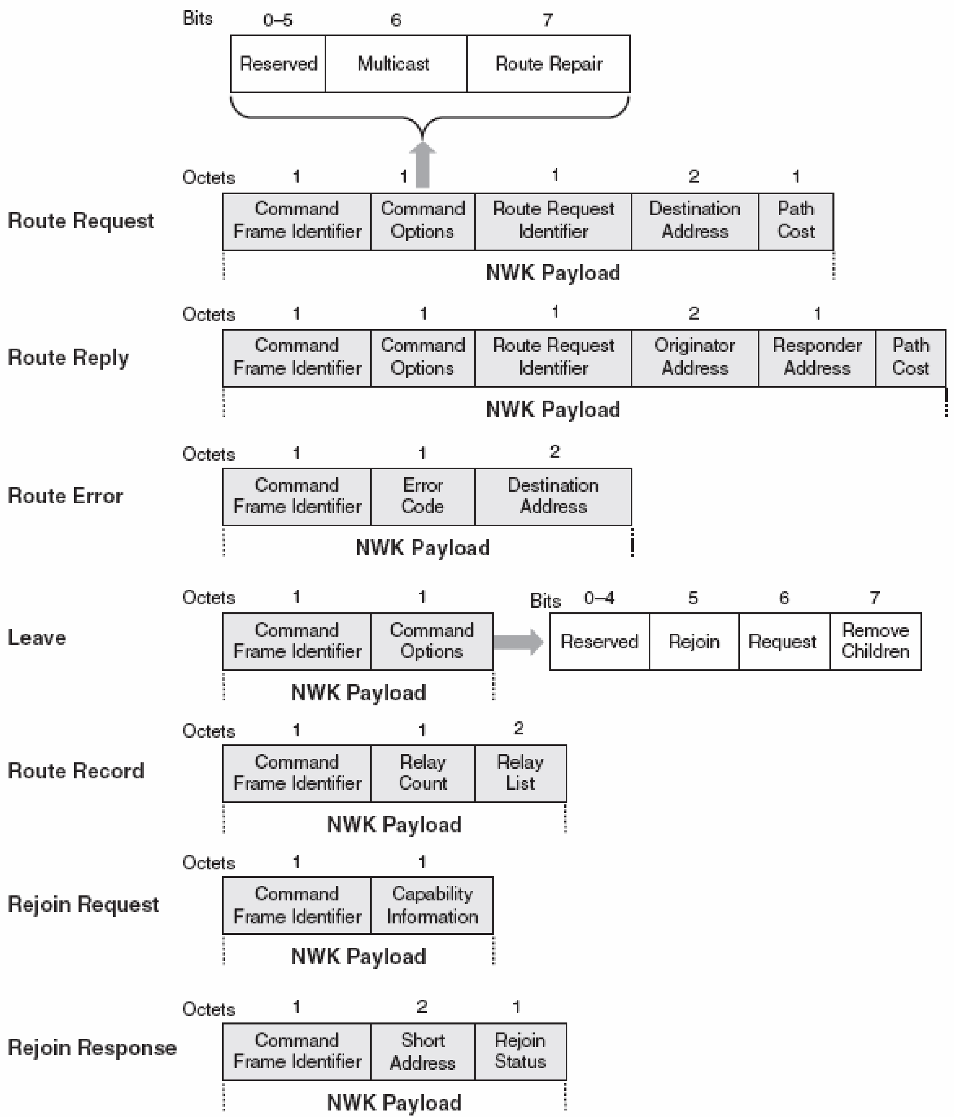


Figure 4.13 - NWK Layer Commands Formats

The data and command frame formats are illustrated in Figure 4.12 .
The routing field is the combination of the fields between the frame control and the NWK payload in Figure 4.11 and the NWK commands are listed in Table 4.5.

Each command is identified by an 8-bit integer value known as the NWK command identifier, together with the command payload will form the NWK frame payload.

The NWK commands are briefly reviewed here. The formats of the NWK layer command payloads in ZigBee 2006 are illustrated in Figure 4.13 .

The first command is the route request command, which is used in the route discovery and route repair procedures described previously (par 4.2).

This route request is part of a multicast route discovery whether the multicast subfield value is set to one.

The route repair subfield is set to one to identify this request command as a route repair instead of a route discovery.

The reason for distinguishing route repair from route discovery is that the route discovery is always initiated by the originator device. The route repair, conversely, is initiated by the router device that has tried to relay the message of the source device but has found a link failure while attempting to send the frame to the next node.

The route request identifier is an 8-bit sequence number used to identify each route request issued by a source node and its value is incremented by one by the source device increments every time it performs a new route request.

During the route discovery process, the routers that broadcast the route request of the source node keep the route request identifier unchanged.

The target of the route discovery is to find a route to the destination address provided. For more information about route discovery see paragraph 3.3.4

In the new ZigBee-Pro, there is one more field positioned after the path-cost field in the route request command: the destination IEEE address. Moreover, in ZigBee-Pro in the command options filed the bits 3 and 4 are used for many-to-one route requests. Whether the route requests is not a many-to-one route request the value of bits 2–3 is equal to 0.

Conversely if the value is equal to 1, the route request is many-to-one and the sender supports a route record table. Finally, if the value of bits 2–3 is 2, the route request is many-to-one but sender does not support a route record table.

Another NWK command is the *route reply* command, which is sent by the destination device to the originator node in response to a route request command. The command option field is very similar to the command option field of the route request command and the route request identifier is the same as the route request command frame. Thus when the originator receives back the route reply command from the target device, the source device will know this route reply command is in response to one of the source device route requests it sent.

The source address field contains the short address (16-bit) of the device that originated the request. The responder address field contains the NWK address written in the route request command destination address. The originator always tries to establish a route to the destination node. In ZigBee-Pro, there are two additional fields after the path-cost field: originator IEEE address and responder IEEE address.

The *route error* command is used to alert the source device about an error in relaying the frame toward a destination address. The error code written in the error code field can be used to determine which is the cause of the error. Possible reasons for routing errors are link failure, lack of routing capacity, and low battery level. Finally, the relaying node is incapable of acting as a router, because of its battery energy critically low.

In the new ZigBee-Pro, this command is renamed to Network Status Command and it contains all the error codes present in route error command plus several additional codes to report incidents like PAN identifier update.

A node will transmit the leave command either when the node itself wants to leave the network or if the node is requesting another node to leave the network. If the device itself is leaving the network, the request field of the leave command is set to zero, it is set to one, instead, to indicate that the sender of this command is asking the target to leave the network.

The node may leave its parent but can rejoin another device in the network, in this case, the rejoin subfield of the leave command is set to one.

At the latter, if the node that leaves the network is a parent and the remove children subfield of the command is set to one to force all the children of this parent to be removed from the network when their parent leaves.

The *route record* command is sent to record the address of all the devices that relay this command frame to the target node via an established route, and the count value will be incremented by one for each time the frame is relayed. The short address of all the nodes that relayed the message is kept in the relay list.

When a node other than the target node receives this record command, it will add its short address to the relay list and then will send it to the next hop provided by the routing table.

If a node loses its connection to the network, it can use the rejoin request command to rejoin the network through a node other than its original parent. The device provides the list of its capabilities within the rejoin request command. This is similar to the capabilities list provided in a MAC layer association request (Figure 3.13).

The node that receives the rejoin request will reply with a rejoin reply command. If the new parent device has the capacity to accept a new child, the short address field in the rejoin reply command will provide the new short address assigned to the child.

The NWK layer in ZigBee-Pro 2007 has three additional commands not available in ZigBee-2006.

The first one is the *Link Status* Command. Each node acting as a router can use the link status command to provide its link-cost to other neighboring routers. The second command is the *Network Report*, which is used to report events such as PAN ID conflict and channel condition to a designated device in the nwkManagerAddr.

The last command added is the *Network Update* Command used by a designated node (identified by the nwkManagerAddr attribute) to broadcast configuration changes. The format of these commands is provided in the ZigBee specification [Zig08]

4.4 The APL layer

The application layer (APL) is the highest layer in a ZigBee wireless network. Most of the works for the design and implementation of our WSN system is done on this layer. Also the compression functions are implemented at this level since the inclusion on NWK layer, together with the encryption algorithm, as lead to the application instability (probably due to the time taken from both functions)

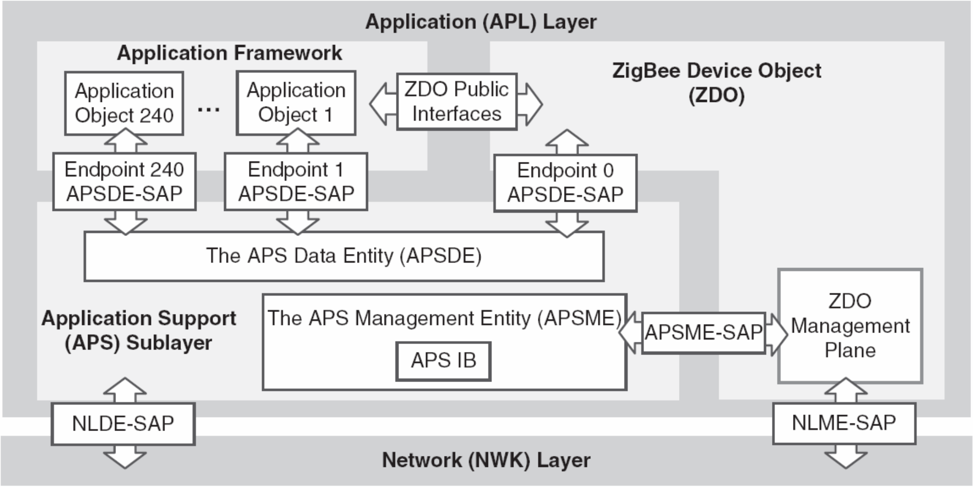


Figure 4.14 - The APL Layer (APS Sublayer, ZDO, and the Application Framework)

The ZigBee APL layer consists of three sections, illustrated in Figure 4.14: the application support sub layer (APS), the ZigBee Device Objects (ZDO) and the application framework.

The APS provides an interface between the network and the application layer. The APS sub layer supports both data and management types of services. The APS Data Entity (APSDE) offers the data services and is accessed through the APSDE Service Access Point (APSDE-SAP).

The management capabilities are provided by APS Management Entity (APSME) accessible through the APSME-SAP.

The APS sub layer constants and attributes start all respectively with the suffix apsc and aps. The APS attributes are contained in the APS Information Base (APS IB or AIB). The list of APS constants and attributes is provided in the ZigBee specification [Zig08].

In the ZigBee stack, the application framework is the environment in which application objects are hosted to control and manage the protocol layers. Application objects are usually developed by manufacturers to fit various kind of applications.

There can be a maximum of 240 application objects into a single device and they use APSDE-SAP to send and receive data between peer application objects (fig. 4.14). Each application object has its own unique endpoint address (endpoint 1 to endpoint 240). The endpoint zero is used to access the ZDO area.

To broadcast a message to all objects the endpoint address must be set to 255. Multiple devices can allow to share the same radio via endpoint addressing. For example if we have a light control application, where multiple lights are connected and share a single radio, in this case each light has a unique endpoint address and can be turned on and off independently.

The ZDO provides an interface between the APS sub layer and the application framework. The ZDO contains all the functionalities that are common to all applications operating on a ZigBee protocol stack.

It is, for example, a duty of the ZDO to configure the device in one of three possible logical types of coordinator, router or end-device.

The ZDO uses primitives to accomplish its duties and accesses the APS sub layer Management Entity via APSME-SAP, while the framework accesses the ZDO via the ZDO public interface.

The details of the three APL subsections are reviewed in the following paragraphs.

4.4.1 The application framework

The ZigBee architecture offers the option to use *application profiles*, also referred to as ZigBee profiles, in developing an application which allows further interoperability between the products developed by different vendors.

For example, in a light control environment, if two manufacturers use the same application profile to develop their products, the switches from one vendor will be able to turn on and turn off the lights manufactured by the second one.

Each profile is identified by a 16-bit integer value known as a profile identifier . Only the ZigBee alliance group can issue profile identifiers, a manufacturer whom has developed a profile can request a new identifier from the ZigBee alliance.

The application profiles are named after their corresponding application use, for instance, the *home automation* profile provides a common platform for manufacturers developing products for home automation.

The structure of an ZigBee application profile is depicted in Figure 4.15. The application profile is built by two main components: clusters and device descriptions. A cluster is a set of grouped attributes. Each cluster is identified by a unique 16-bit value named cluster identifier . Each attribute in a cluster is also identified by a unique 16-bit integer known as a attribute identifier. These attributes are used to store data or status values such as in a temperature control application, a device that acts as the temperature sensor can store the value of the current temperature in an attribute, then another device that acts as the heater controller can receive the value of this attribute and, accordingly, turn on or turn off the heater.

The application profile does not contain the cluster itself, instead, the application profile has a list of the cluster identifiers. Each cluster identifier uniquely points to the cluster itself.

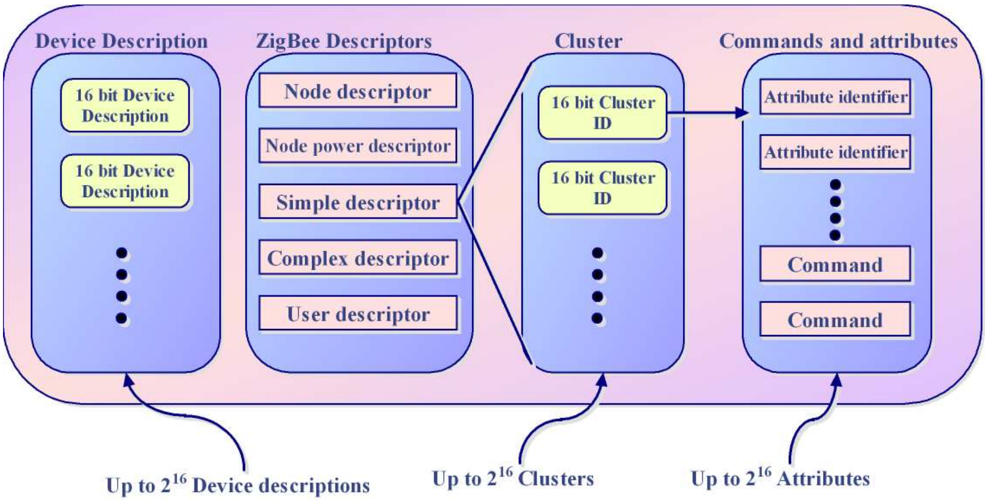


Figure 4.15 - The application profile

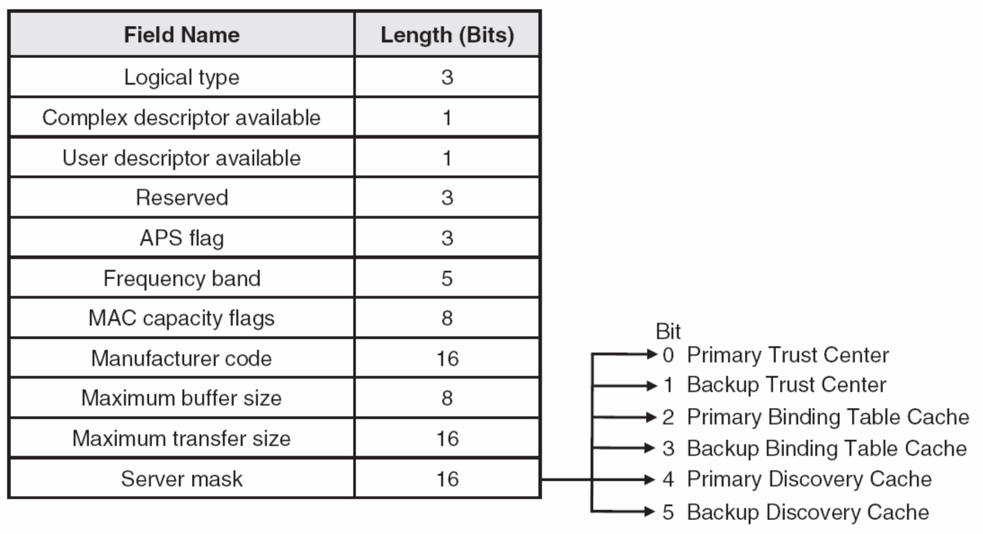
The second part of an application profile is the device descriptions (Figure 4.15). The descriptions supply information regarding the device itself such as the supported frequency bands of operation, the logical type of the device (PAN coordinator, router or end device), and the remaining battery energy Again a 16-bit number identify each device description.

The application profile uses the descriptor data structure where, instead of including the data in the profile, a 16-bit number is kept and provides a pointer to the data location (called data descriptor).

The device descriptions consist of five fields: node descriptor, node power descriptor, simple descriptor, complex descriptor and user descriptor. The node descriptor provides information such as the node logical type and the manufacturer code. The *node power* descriptor determines whether the device is battery powered and stores the current battery level.

The profile identifier and clusters are provided in the *simple descriptor,* while the *complex descriptor* is an optional part containing information like the serial number and the device model name, any additional device information can be included as the user descriptor.

The *user descriptor* can be up to 16 ASCII characters. For example, in a light control application, the user descriptor field of a wall switch installed in a room can read “bedroom switch” .



Field Name	Length (Bits)
Logical type	3
Complex descriptor available	1
User descriptor available	1
Reserved	3
APS flag	3
Frequency band	5
MAC capacity flags	8
Manufacturer code	16
Maximum buffer size	8
Maximum transfer size	16
Server mask	16

Bit	
0	Primary Trust Center
1	Backup Trust Center
2	Primary Binding Table Cache
3	Backup Binding Table Cache
4	Primary Discovery Cache
5	Backup Discovery Cache

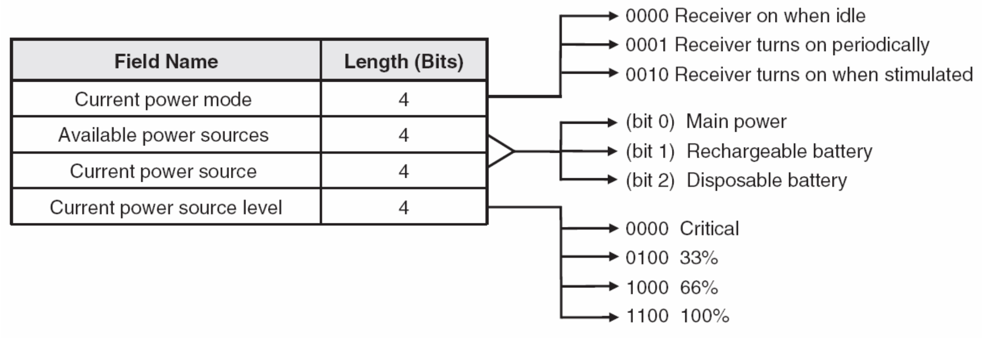
Figure 4.16 - Node descriptor fields

The node descriptor fields for ZigBee-2006 are shown in Figure 4.16. The *node descriptor* is a mandatory part of the device descriptions:

- The *logical type* can be coordinator, router or end-device.
- The *complex descriptor* and user descriptor are optional and if their corresponding fields in the node descriptor are set to zero, they are not given as part of the device descriptions.
- The APS *flag field* determines the APS capabilities.
- *frequency band* (868 MHz, 915 MHz, or 2.4 GHz) is specified in the frequency band field.
- The *MAC capacity flags* field is the same as the MAC capacity field presented before in Figure 3.14. A manufacturer can request and receive a manufacturer code from the ZigBee alliance. This code is included in the node descriptor.
- The *maximum size* of the APS Sublayer Data Unit (ASDU), in octets, is specified in the maximum buffer size field. The maximum size of a single message that can be transferred to or from a node is provided in the maximum transfer size field (in octets). In ZigBee-Pro, the maximum incoming transfer size and maximum outgoing transfer size are two separate fields (16 bits each).
- The *server mask* field supplies information regarding the server capabilities of this node. A server is a node that provides specific services to other devices in the network. If each bit is set to one, the device has the corresponding capability depicted in Figure 4.16
    - The *trust center* is the node trusted within a network to distribute security keys for the purpose of network and end-to-end application configuration management. The security features are reviewed further in this chapter.
    - The *primary binding table cache* is a node that allows other devices to store their binding tables with it as long as it has storage space left. The primary binding table cache can be used to back up the content of binding tables and restore them whenever necessary.
    - A ZigBee network may have a *primary discovery cache* node such as a coordinator or router used to store information such as node descriptors and power descriptors of some other devices which, for example, sleeps for long time.

If a network contains sleeping devices, the network must have at least one primary discovery cache node. The node power descriptor fields are shown in Figure 4.17. The receiver can stay in ON mode while the node is in idle but this is not a power aware solution.

Alternatively, the node can turn on the receiver periodically.
The last option is to turn on the receiver using an external trigger event upon an incoming message. As described in fig. 4.17 the node may have multiple power sources and for each power source available the corresponding bit in the available power sources field is set to one.



Field Name	Length (Bits)
Current power mode	4
Available power sources	4
Current power source	4
Current power source level	4

0000 Receiver on when idle
0001 Receiver turns on periodically
0010 Receiver turns on when stimulated
(bit 0) Main power
(bit 1) Rechargeable battery
(bit 2) Disposable battery
0000 Critical
0100 33%
1000 66%
1100 100%

Figure 4.17 - Node power descriptor fields

For instance, if the node has both main power and rechargeable battery, the available power sources field will read 0011.

Field Name	Length (Bits)
Endpoint	8
Application profile identifier	16
Application device identifier	16
Application device version	4
Reserved	4
Application input cluster count	8
Application input cluster list	16 · i (i =input cluster count)
Application output cluster count	8
Application output cluster list	16 · o (o = output cluster count)

Table 4.6 - Simple descriptor

Table 4.6 shows the list of simple descriptor fields. The *endpoint* field contains the endpoint address of a node. The *application profile identifier* that is supported by this endpoint is in the application profile identifier field.

The device description supported by this device is specified by a 16-bit number supplied in the application device identifier field. The device description may change over time, and the application device version field determines which version of the device description is supported by this node. All the cluster identifiers supported by the device are included in the simple descriptor.

Figure 4.18 show how the cluster identifiers (clusterIDs) are used in binding relationships. Binding is the task of creating logical links between applications that are related. Devices logically related in a binding table are called bound devices .

In fig 4.18 two switches share the same radio and they also share the IEEE address and network address. The switches are distinguished only by their different endpoint addresses.

Each switch can have its own application object and each application object can be accessed independently through its corresponding endpoint address. These two switches control three separate lights which are also connected to a single radio and each light has a unique endpoint address.

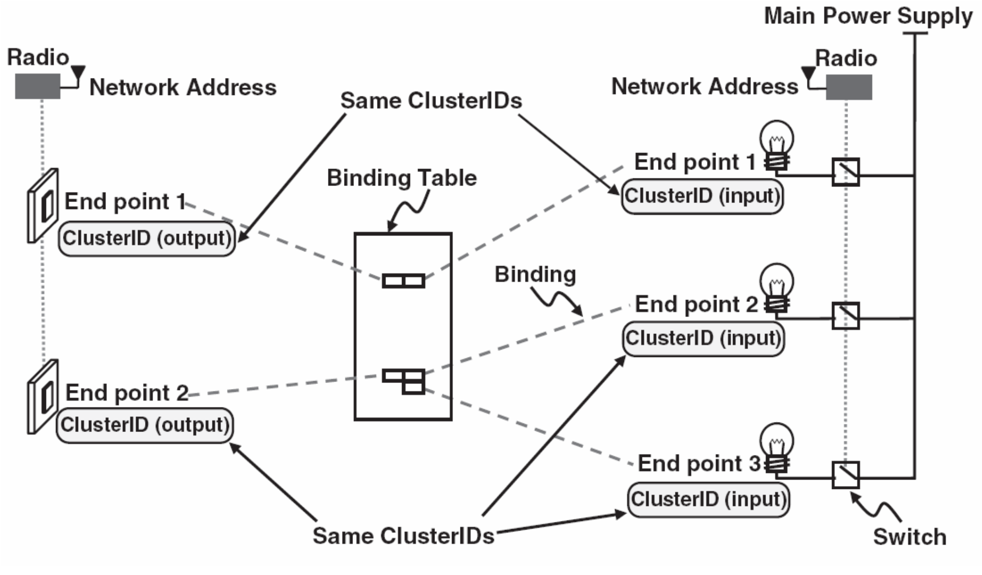


Figure 4.18 - The binding relationships

A cluster can be an *input cluster* or an *output cluster* therefore, in the binding process, two devices are matched if both devices have the exact same clusterIDs but one is an input cluster and the other one is an output cluster.

The wall switch at endpoint 1 and the lamp at endpoint 1 have the exact same clusterIDs and so they are considered bound devices. The wall switch at endpoint 2 is bounded to both lamps at endpoint 2 and endpoint 3. The information regarding these logical links is stored in a binding table.

The bind itself can be created by the installer. For instance, the installer can push two physical buttons: one on the wall switch and one on the light itself to create the bind between these two devices. This would create an entry in the binding table corresponding to these two devices.

More specifically, pushing the button on the wall switch initiates the transmission of the end device bind request command (*End_Device_Bind_req*) to the PAN coordinator.

This command is part of the device profile discussed in the next paragraph. The PAN coordinator, upon receiving this command, waits for a period of time to receive the end device bind request command from the light.

If this bind request arrives before the timeout period, the PAN coordinator matches these two devices based on their profile identifier and the list of their input/output clusters.

This is called simple binding mechanism. In simple binding, user intervention is used to identify the device pairs.

4.4.2 The ZigBee device objects

Figure 4.19 illustrates the ZigBee Device Objects (ZDO) space as an interface between the APS sub layer and the application framework.

The ZDO has the tasks of initializing the APS, NWK, and Security Service Provider (SSP). As for the application profiles defined in the application framework, there is a profile defined for the ZDO which is known as the ZigBee Device Profile (ZDP) or simply the device profile.

The ZDP contains device descriptions and clusters, but the device profile clusters do not use attributes.

The ZDO has configuration attributes, but these are not included in the device profile. Another difference between the device profile and any application profile is that the application profile is created for a specific application, the device profile, instead, defines capabilities supported by all ZigBee devices.

The device profile includes only one device description while the clusters are divided into a mandatory group and an optional group. The mandatory clusters must be implemented in any ZigBee device and the device profile furnish support for device and service discovery besides binding management.

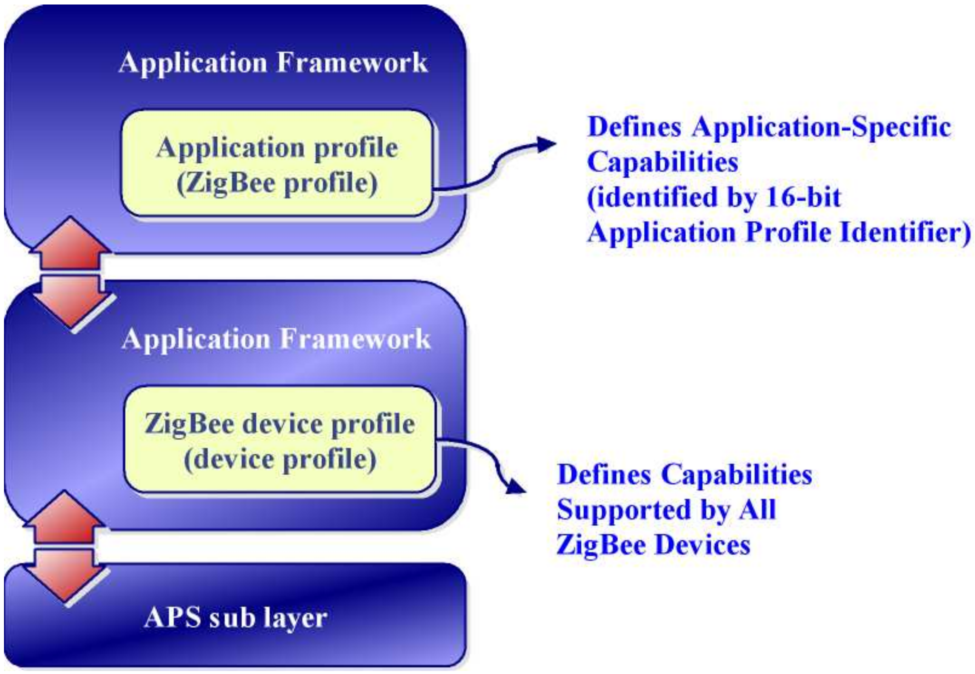
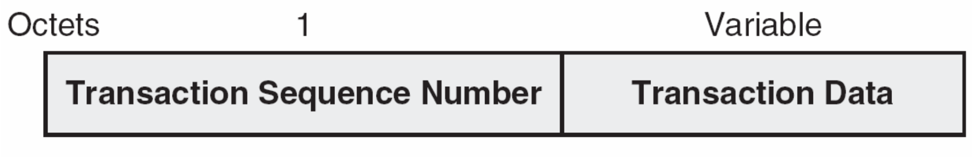


Figure 4.19 - The ZDO Acts as an Interface Between the Application Framework and the APS Sublayer

In service discovery, the ability to determine the identity of other devices on the PAN, the device requests that another device in the network supplies detailed information like its profile identifier or its ZigBee descriptors. The device can also ask the list of input and output clusters of another device and this cluster list provided can be used to match devices in the binding procedure.



Octets	1	Variable
	Transaction Sequence Number	Transaction Data

Figure 4.20 - The ZigBee Device Profile Command Format

The device profile can be configured to be a client, a server or both.

A client is a node that asks a service such as device discovery or binding while the node that responds to the request and providing the service acts as a server.

Thus the services offered by the device profile are divided into client services and server services. Both these services are provided in the form of commands with unique cluster identifiers (clusterIDs), for instance, the clusterID of 0x0002 in the device profile is equivalent to the *Node_Desc_req* (node descriptor request) command, which is used to request the device descriptor of another node.

In message exchange between the client and the server, the client is referred to as the local device and the server is known as the remote device.

The ZDP commands are sent using the APS data service which has a format shown in Figure 4.20.

The first part is an 8-bit transaction value, thus means that any application object maintains a counter and increments it every time a new transaction is sent. The content of this counter is put into the transaction sequence number field of the ZDP command. The transaction data contains the command itself and all data associated with the command.

The complete list of ZDP commands and brief descriptions of the commands are provided in Appendix C.

The commands are divided in client services and server services commands group. In each group, the ZDP commands, are divided in three sub categories: device and service discovery, network management and bind management. The commands in these categories form three distinct objects in the ZDO: the device and service discovery object, the network manager object and the binding manager object.

The service discovery commands allow a device to ask information such as NWK address and list of descriptors of any other node in the network.

They also allow a device to store its own descriptors in a primary discovery cache device or configure the user descriptor of another device in the network.

The bind management commands allow a node to create or remove binding relationships, store binding tables on a primary binding table node, create backup binding tables, and recover previously stored backup binding tables.

The network management commands, instead, are used to identify nearby networks and manage joining and leaving nodes in the network.

The ZDO contains two more objects: the network manager and the security manager.

The network manager contains the networking-related functions to interface with NLME (like NLME-JOIN.request). The security manager object contains security-related primitives to interface with the APS sublayer

Management Entity (APSME). Both these objects are discussed later in this chapter.

The configuration attributes contained in ZDO start with Config _ and they are not related to the ZigBee Device Profile but contain information such as node descriptor and the network security level.

The complete list of the ZDO attributes is provided in the ZigBee specification document [Zig08].

4.4.3 The APS sublayer

The APS sub layer supplies data services to both application objects and ZigBee Device Objects through the APS sub layer Data Entity (APSDE). The APSDE receives the data that needs to be sent in the form of a Protocol Data Unit (PDU) from either ZDO or an application object.

The APSDE adds headers to the PDU to create an APS data frame, which will be passed to the NWK layer.

The APS sub layer Management Entity (APSME) contains primitives to perform bind management, APS Information Base (AIB) management and group management tasks.

The binding functions (*APSME-BIND.request* and *APSME-UNBIND.request*) enable the higher layer to request to bind two devices by creating an entry in the binding table or to unbind two devices by removing the corresponding entry from the binding table.

The APSME-GET.request and APSME-SET.request primitives allow the next higher layer to read and write attributes in the APS Information Base. The group management primitives are used to add or remove endpoints of the node in a group table.

Besides unicast, broadcast and multicast delivering message methods a fourth option is available by the APS sub layer and is known as *indirect addressing*. In the indirect addressing a node with limited resources that is bound with other nodes in a network can communicate without knowing the address of the desired destination.

Indirect transmissions are sent to the PAN coordinator by the source device and the coordinator itself looks up the source address, endpoint address, and clusterID from its binding table and retransmits the message to each corresponding destination address/endpoint.

Figure 4.21 is the APS frame format in ZigBee-2004/2006. In ZigBee Pro, there is an optional field called *Extended Header*.

There are a total of three different types of APS frame: data, command, and acknowledgment.

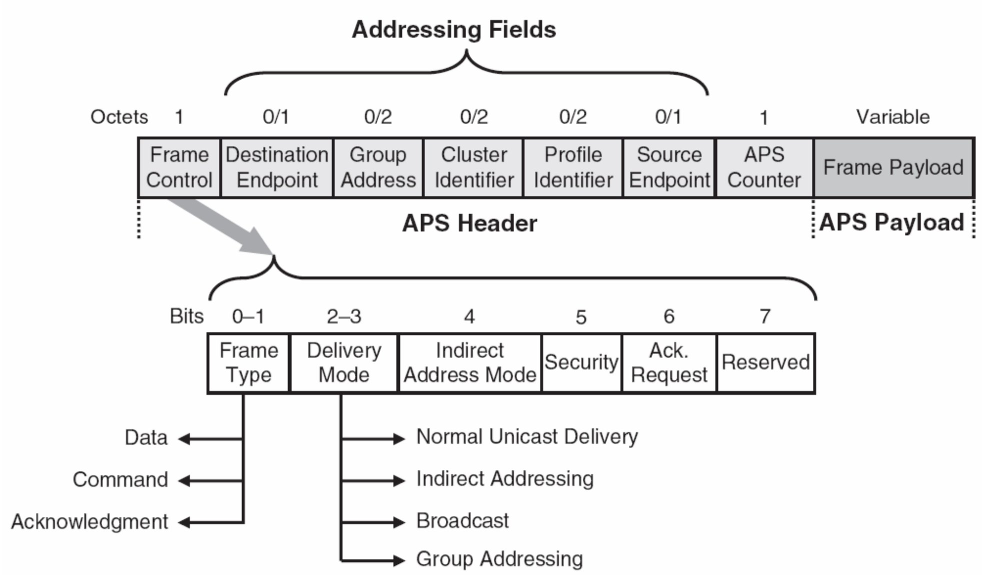


Figure 4.21 - General APS frame format

The *frame type* subfield in figure 4.21 determines, as the name suggests, the type of the frame.

The *delivery mode* value indicates the transmission options. If the delivery mode is the indirect addressing, the *indirect address mode* subfield specifies which address field (source or destination) must be omitted from the frame and if is set to one means that the frame is intended for the ZigBee coordinator (destination endpoint must be omitted). If this field, instead, is set to zero, this frame is being sent from the ZigBee coordinator to the destination (source endpoint must be omitted).

The Security Service Provider (SSP) set the security subfield value. If the acknowledgment request attribute is set to one, the destination of the frame must send an acknowledgment back to the originator.

If a group address is selected, the message will be sent to all endpoints that are members of the group. The destination endpoint field and the group address field cannot be present together in one frame.

The cluster identifier field is only present in a binding operation and contains the cluster identifier that will be used in the binding procedure.

The APS counter is an 8-bit counter added to every APS frame and incremented by one each time a new frame is transmitted. This counter helps to identify and to ignore the duplicate frames.

Figure 4.22 illustrates the APS frame types. The data frame has the same format as a general APS frame.

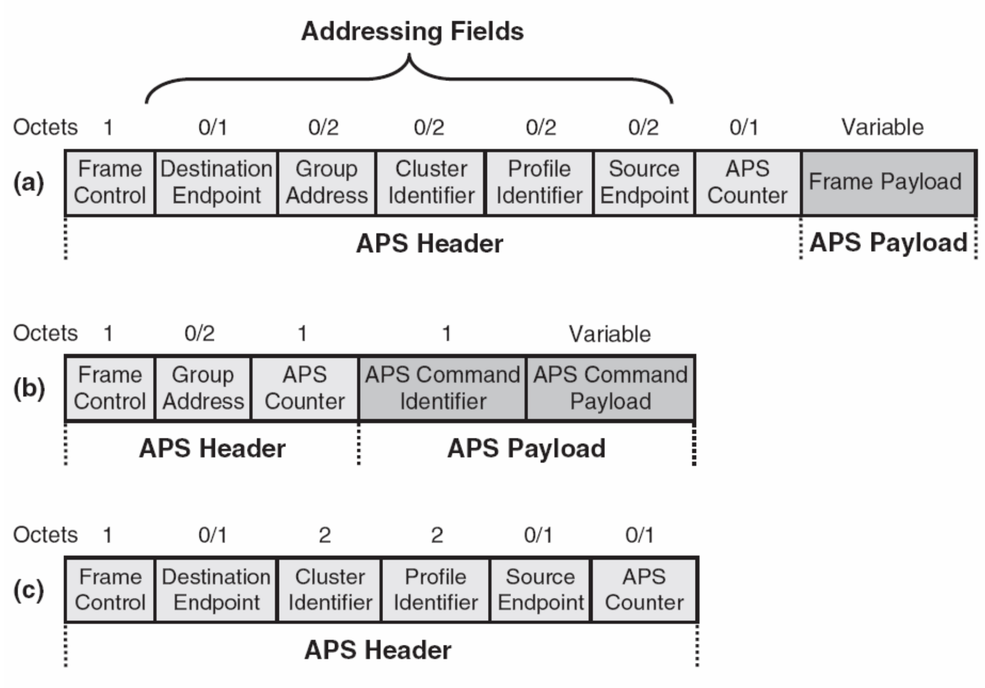


Figure 4.22 - APS layer: (a) data frame, (b) command frame and (c) acknowledgment frame formats

4.5 Security

The Security in the ZigBee standard is one of the aspect that were improved by each new set of specification. This is a clear sign of how important is considered this aspect and how much it is currently considered unsatisfactory. In fact many security flaws were found in all version of ZigBee and was an important part of our application work (e.g. in the paragraph 5.6 is presented a way to steal the AES key from the nodes).

ZigBee-Pro supports additional security features that are not available in ZigBee-2006 nor in ZigBee 1.0.

In ZigBee-2006, there are nine APS security commands while in ZigBee-Pro in addition to the commands supported in ZigBee-2006, there are five more commands.

One of these additional commands, the *Tunnel* command, allows a device to send a command to a device that does not have the current network key. The other additional commands are used for entity authentication, which allows two nodes to authenticate each other.

These two nodes must share a common security key. Each device creates a 16-octet random string called *random challenge* and sends this challenge to the other device.

Entity authentication is not supported in ZigBee 1.0 and -2006. In version 1.0 there is only tone level of security, in ZigBee-2006, instead, the trust center can operate in *commercial mode* or *residential mode*. Commercial mode has a higher security level than residential mode. For instance, in commercial mode, the trust center must maintain a list of nodes, master keys, link keys, and network keys while in residential mode, only the network key must be saved.

ZigBee-Pro uses the same concept but renames the commercial and residential modes of operation to *high security and standard security* modes respectively. In ZigBee 1.0 every device must share the same base key, In ZigBee-2006, the trust center is assumed to be located on the ZigBee coordinator. The trust center in ZigBee-Pro can be positioned on any device.

Among all the research issues, security is an essential requirement in WSN environments.

Compared to wired networks, WSNs are more vulnerable to security attacks due to the lack of a trusted centralized authority, lack of trust relationships between mobile nodes, easy eavesdropping because of shared wireless medium, dynamic network topology, low bandwidth, and battery and memory constraints of mobile devices.

The security issue of WSNs in group communications is even more challenging because of the involvement of multiple senders and multiple receivers.

Although several types of security attacks have been studied in the WSNs literature, earlier research is focused on unicast (point-to-point) applications. The impacts of security attacks on multicast in WSNs have not been explored yet [CeC09].

For a complete classification of security attacks (and attackers) see the Appendix A

5

Design and implementation of a WSN

5.1 Selection of the developer kits

Nowadays many Developer kits are available worldwide and their number will probably increase in the future.

When the my research project started more then 25 companies were proposing their own kits. The WSN Developer kit choice was made evaluating many features, including, but not limited to:

- microcontroller characteristics (memory, computing power, number and capacity of A/D lines, bus type)
- Overall Power consumption and battery type
- On-board sensors
- Bus expansion capacity (type and number of bus)
- Developer software and licence
- Development assistance
- Kit’s price and single node’s price

Some manufacturers had more than just one single kit or kind of node to cover a wider range of application development needs.

In Appendix B are compared the best fitting solution from any manufacturer, considering the type, the number of node and software included, just to simplify the reading, because of the complete Synoptic table includes over 70 kits.

The final choice was made considering, as required features, the node capacity to work in different environments and the possibility to connect different kind of sensors through different type of bus, rather than the node size itself.

The chosen nodes, although their relatively small size (Size 60 x 63 x 24 mm), have both USB and serial connection, several expansion bus such as

I^{2}C, SMBus, SPI, UART e USART easily usable via a standard JTAG compatible connector. They use two, the easy-to-find, AA batteries and may be also connected to a power supply (included in the kit).

Although they did not have any unique feature respect others nodes they were a right balanced between board size, bus expandability and energy features.

Another very important kit's feature was the software included and the licence type. Open source software or free of charge integrated development kit were preferred to proprietary solutions as well as the support from the manufacturer developer team support was considered one of the most appreciate feature.

The support was tested in advance via e-mails where were asked many technical information about the nodes' architecture and performance and the software solution provided within the kit. The quality of the answer, as well as the time elapsed since the initial request was sent, was taken in high consideration for the estimation of the technical support.

Occasionally some interesting kit were found to be only an "advertising". For example an all inclusive software kit with 5 nodes without sensors at the amazing low price of 199,00 dollars, never appeared in stock to any vendor official worldwide distributor.

Is it to be underlined that all prices quoted in this work must be considered as indicative, subject to changes and referred to the specific period (the first project month) in which the WSN kit had to be chosen.

These kind of events may be typical for every quick tech market that didn't yet find its own identity and target.

After a careful comparison between the kits we have finally chosen the Meshnetics ZigBit Development Kit described in the next paragraph. As noted before, this doesn't mean that the kit chosen is the definitive solution but just as good as a starting point at beginning of our research project.

5.2 Meshnetics starter kit

The Meshnetics ZigBit Development Kit is a simple solution designed for WSN development.

It provides development boards based on the ZigBit module and eZeeNet Software to test the wireless network features and develop customized wireless solutions.

ZigBit Development Kit includes:

- MeshBean2 board (3 pieces) with ZigBit module and (PCB, SMC and dual-chip) antenna
- AC/DC power adapter (3 pieces) with USA and European connectors
- USB cable (3 pieces)
- RS-232 cable (2 pieces)
- Software & Documentation CD (1 piece).

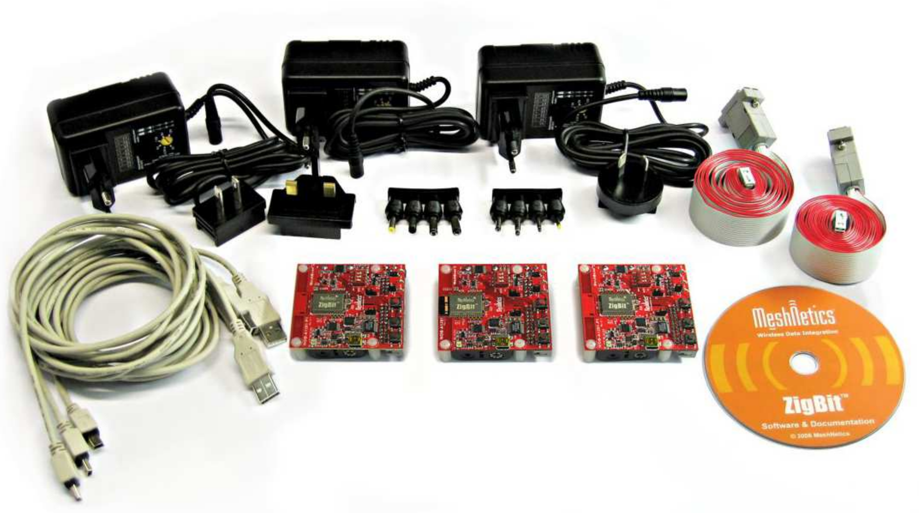


Figure 5.1 - The Development Kit delivery set

The ZigBit module with the eZeeNet Software provides the MeshBean2 board’s wireless connectivity and makes it function as a node in a ZigBee network.

The MeshBean2 board is a full function device (see chapter 3.3..1 for more information about ZigBee device) and can be configured to operate as a network coordinator, a router or an end-device.

A manual configuration is allowed by the on board DIP-switches and/or sending AT commands.

The node’s role is defined by the embedded developed applications.

The boards are delivered with a firmware containing an Hardware Test software and a Serial Boot loader. The boot loader allows the serial connection to be used to write the new developed software into the node without the need to buy a microcontroller programmer.

The programmer is still needed if something happens to the boot loader or if something special, like the software and cryptographic key protection is implemented.

The boot loader corruption seems to happen on battery replacement, the reason may be an electric peak. Although it’s a very rare event, nothing can be done without the Atmel programmer’s board.

5.2.1 Hardware general specification

MeshBean 2 basic parameters are presented in Table 5.1b, the boards, as well as all the ones shown above, are provided with the following features:

- Size 60 x 63 x 24 mm
- Over-Voltage Protection
- Reverse Polarity Protection
- 3 programmable color status LEDs
- external power supply status LED
- Switches 3 DIP switches
- 2 programmable buttons
- 1 reset button
- Operating Temperature Range: -40°C to 85°C. Minor degradation of clock stability may occur beyond the -20°C to +70°C range

The board uses light sensor TSL2550T from TAOS (see [10]) and temperature sensor LM73CIMK (see [11]) from National Semiconductors. Both sensors are connected in parallel to the I2C bus.

An USB to RS-232 bridge controller CP2102 from Silicon Labs is installed on the board and provides seamless USB interface (see [12]).

As a result the USB port is visible as generic COM port with a particular number. The driver set for Windows and other operating systems can be easily downloaded from the manufacturer’s website (silabs)

5.2.2 MeshBean2’s expansion connectors

The MeshBean2 board contains several interfaces on the Expansion Connector.

The board includes the following interfaces:

- USB 2.0 port
- RS-232 interface
- Buffered I2C interface with ESD protection and voltage level translation
- Symmetrical dipole PCB antenna
- JTAG connector for software download and debugging

- Power connector (3 V)
- 20-pin expansion connector to access specific interfaces
- Battery compartment for AA-size batteries
- 3 clamps for power consumption measurements

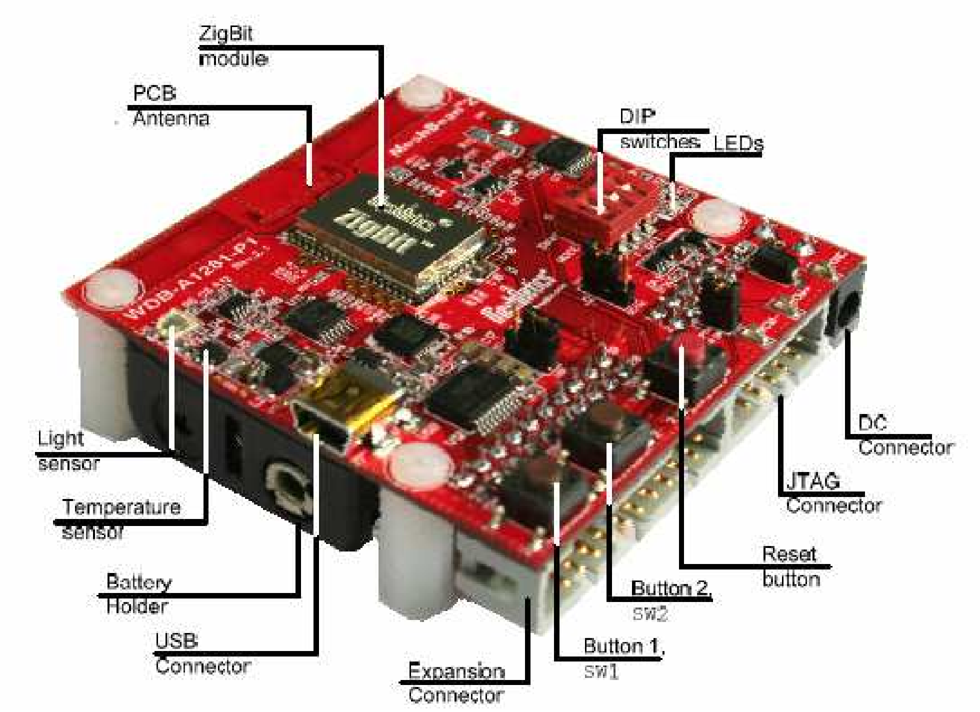


Figure 5.2 - MeshBean2 with PCB on-board antenna

Also, the board contains an internal voltage regulator to supply most of the components with 3.6 V. This is needed if ZigBit's MCU is to be run at 8 MHz.

5.2.3 eZeeNet functional diagram

The software included in the kit is called eZeeNet and is a IEEE802.15.4/ZigBee library stack that runs on ZigBit modules.
It is specifically tailored for easy-to-use networking in sensing, control, monitoring and data acquisition applications and it claims to provide easy to use networking, with a routing mechanism that optimizes network traffic and reduces power consumption.

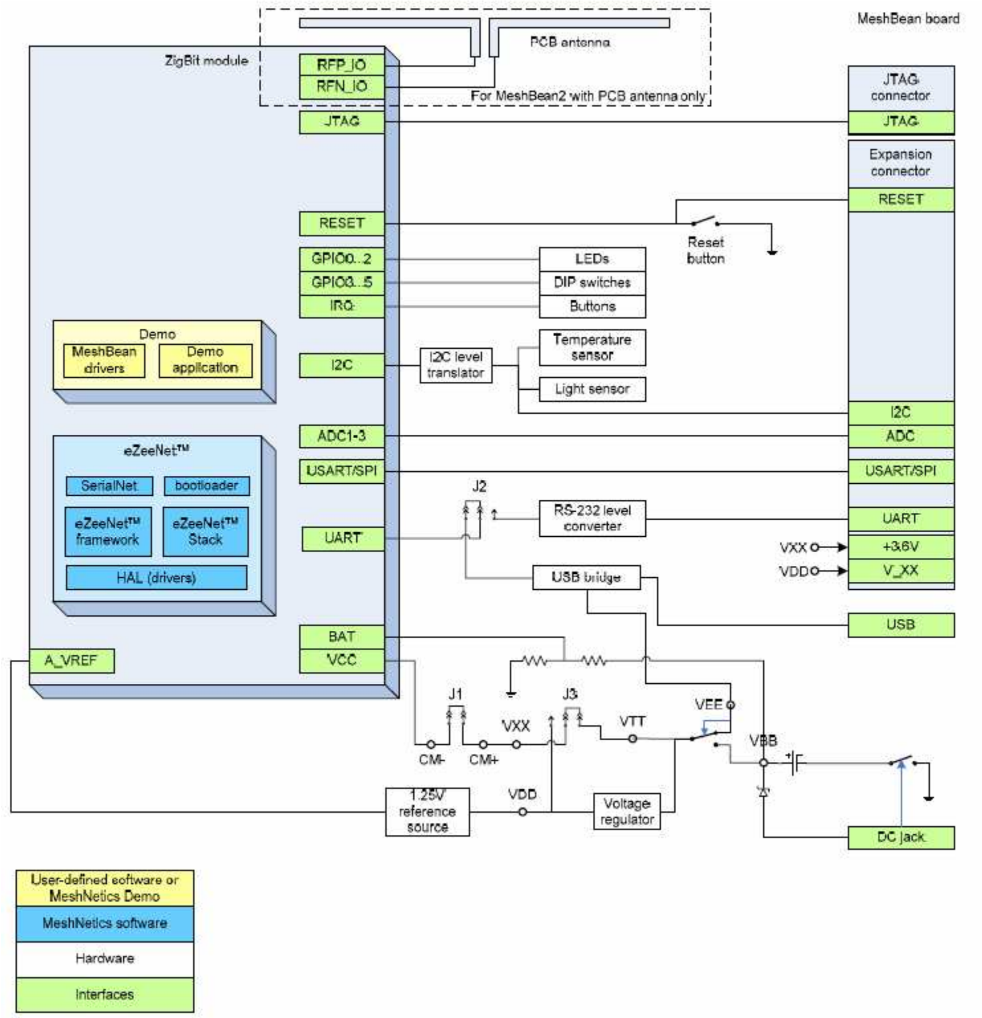


Figure 5.3– MeshBean2 node

eZeeNet Software offers a API for network and smart power management, including data exchange, network formation/node join, PAN ID management, channel selection, TX power control and many others features. It comes with the Framework layer which eases application development and simplifies integration and offers opportunity to develop user's own applications based on the eZeeNet API.

In the ZigBit Development Kit, using the API makes it possible to program the target devices for a variety of WSN application scenarios.

For example, an end-device can be configured to communicate with a router between the periods of sleep thus saving power.

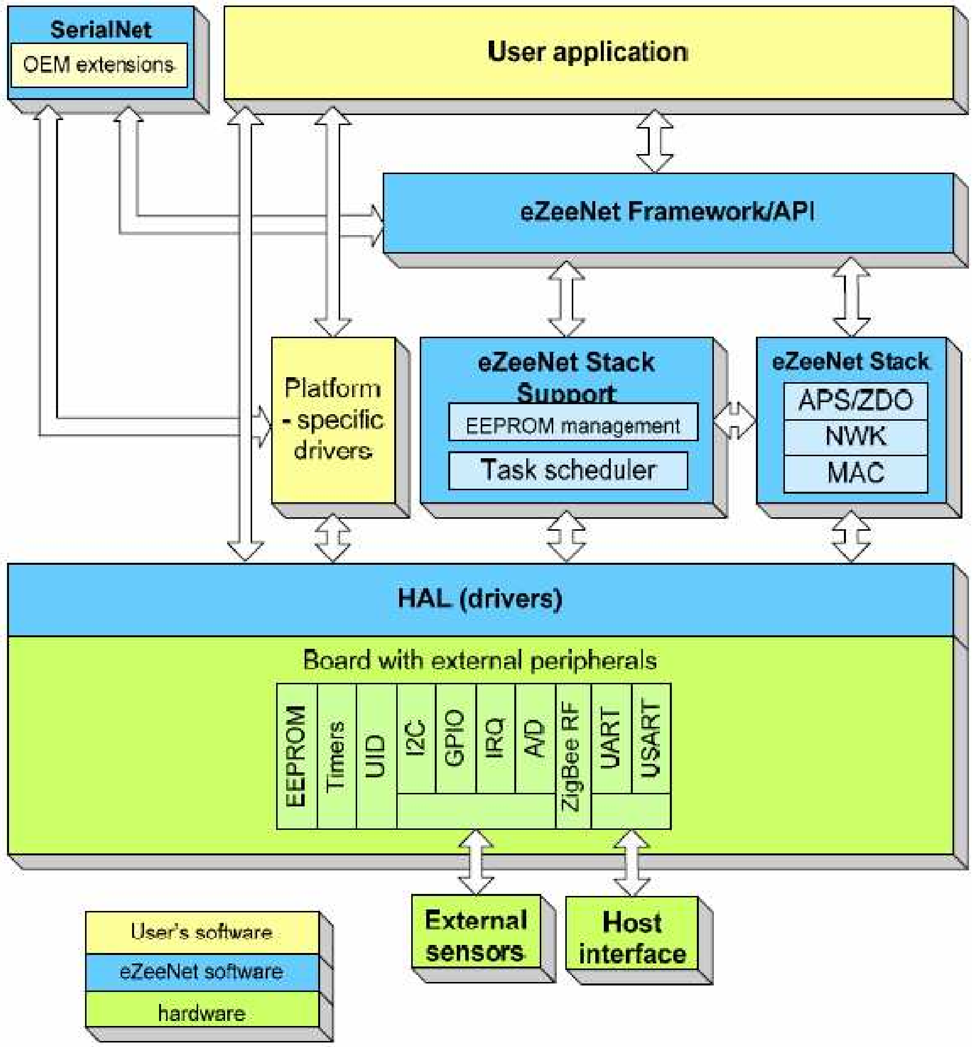


Figure 5.4 - eZeeNet Block Diagram

The SerialNet feature is claimed to enable the user to develop customized WSN applications sending AT Commands without programming the modules directly or writing any embedded software. Although this is, indeed, a little too optimistic, the AT commands can really help sending configuration's parameters to the running nodes without the need to reprogramming the boards and, maybe, restart the nodes or the entire network.

The structure of eZeeNet Software is presented in Figure 5.4.

5.2.4 EZeeNet API

In Figure 4.4 is shown the eZeeNet Stack architecture.

Through the Framework interface several function are managed such as user’s Hardware Abstraction Layer (HAL) and the user‘s application initialization, user’s loop is call, system time, EEPROM and eZeeNet parameters.

The stack interface provides the network management and data transmission’s control.

Data can be transmitted using logical or network addressing. As advantage, logical address of a node is not fixed. Logical addressing is preferable when the address of each node is known in advance, or the addresses can be preset during the commissioning procedure. As disadvantage, address conflicting may happen and should be solved manually or by dedicated software running on coordinator node.

NWK addresses are allocated and changed dynamically. NWK addressing scheme is only recommended for initial network addressing setup, when application receives data from some unknown node, or when several nodes in the network have to use the same logical address. This would be the way to solve address. NWK addressing can be also used in wireless network where data is collected at a sink and no data should be transmitted back. In that case logical addressing is not required, because NWK address is known for coordinator and it equals to zero.

The HAL interface provided in source code can be modified to implement user-defined drivers and to manage specific peripherals. The particularly configured HAL API, the MeshBean2 board interface provides reading the DIP-switches and button control status and LED manipulation.

The interface of eZeeNet is C-callable but mixing C code and user’s C++ code is not guaranteed and must be avoided.

User’s application should follow the register conventions for C-callable functions and the developed applications should avoid to modify the peripheral registers directly. eZeeNet HAL drivers are also C-callable, but some functions can be called only from Interrupt Service Routines (ISRs).

Some functions can be defined as callback handlers. They are used to indicate the completion of some process such as data transmission or they serve as event handlers.

eZeeNet does not call user’s functions directly from ISRs, so the defined callback functions do not need to save/restore the previous context. There are many exceptions due to the performance reasons.

5.2.5 State after reset

The software is allowed to check the reason of the node's reset. As specified in the ATmega1281 datasheet [Atm06], all pins are tri-stated after any kind of reset. But, when the SerialNet (the Serial boot loader) runs, it configures some pins during the start-up phase accordingly to the configuration values stored in the EEPROM. See table B.3 (appendix B) for more information.

As can be imagined, the application must be aware of the reset state and reconfigure the MCU accordingly.

5.3 Development of application code

Before starting the design work we must be aware of the software limitations. This second generation WSN device does not own much resources and the ZigBee stack library occupy most of the available space

The software size problem looks like a knapsack problem (combinatorial optimization problem where a set of items must be included in a collection so that the total weight is less than a given limit), where we have to balance the features we add regarding the memory space(and computing).

In our case the most important features will be, in order of their importance:

- The sensor measurements. The application, of course, to be useful must gather data even regardless the node problems (e.g. node unuble to join the network)
- System disappearence and non interfearence with the people living/working in the enviroment. The lack of study in inhabited enviroment is usually due to the confort issues generated by a monitorig system.
- The battery lifetime so that the system can be unuttended for long periods (this also help to achieve the previous point)
- The flexibility (sensor must be changed/swapped/detached without). This help to increase the usability of the system without a n IT staff intervention
- Security (it may also help to increase the inhabitants' perceived comfort)
- System performance. The better are the performance the greater are the number of application field for the WSN system

Must be noted that security is not in a higher position due to the lack of security of the previously used systems (e.g. the iButton sensors our research centre used in many of our study does not allow any kind of security to be activated).

5.3.1 General Software Specification and user code limitations

Software resource usage is summarized in Table 5.1.

Section name	Section size
Code	96K
Data	6K
Stack	1K

Table 5.1 – Available application's resource

These numbers are valid for the following network configuration:

- *Maximum child number*: **5**
- *Maximum network depth*: **5**
- *Maximum PAN descriptor* numbers (for network discovery): **5**.

The multitasking model used in the eZeeNet software imposes some limitations on the user's code:

- eZeeNet functions must not be called directly from ISRs, Instead, buffer the data and post the TinyOS task by *TOSH_post()* function.
- data processing in the ISR should be avoided.
- disable interrupts for a short time (no more than several tens of microseconds) to provide normal operation of the ZigBee stack and hardware interfaces like UART.
- C-library functions calling or floating-point manipulations in the ISRs must be avoided.
- The user's code limitations shown in table 4.6, it's strongly recommended to follow this size restriction as violation would make stack corrupted.
- stack size must be kept as low as possible.
- All kind of dynamic allocation of the memory by malloc()/calloc()/free() functions must be avoided in the working phase of the software due to the unpredictable processing time and

possible garbage collection problems (if the order of the allocation and freeing is not proper). Usually, allocation should be done at the initialization phase.

- The posting of multiple tasks should be avoided. Instead, the code can be organized in form of infinite loop and check your status variables in the beginning of the loop (it is a MCU typical way o programming).
- The code/data size must be checked before running the application. To determine the size of an application image file correctly can be used the avr-size utility which comes with AVR Tools [Wed06]. If a part of the code is located higher than 0xFC00 address (which seems the address of boot-loader itself) , then it will not be downloadable with Serial Boot loader. In this case the code must be loaded via JTAG only, disabling UART booting by proper fuse bits.
- Although user’s application may use standard C-library, most functions of this library are not guaranteed to be re-entrant. In particular, several functions store local state which are known to be non-reentrant. An example of non-reentrant functions are those that manipulate IO registers, like the EEPROM access routines. Using these functions within interrupt context will result in an unpredictable behaviour.

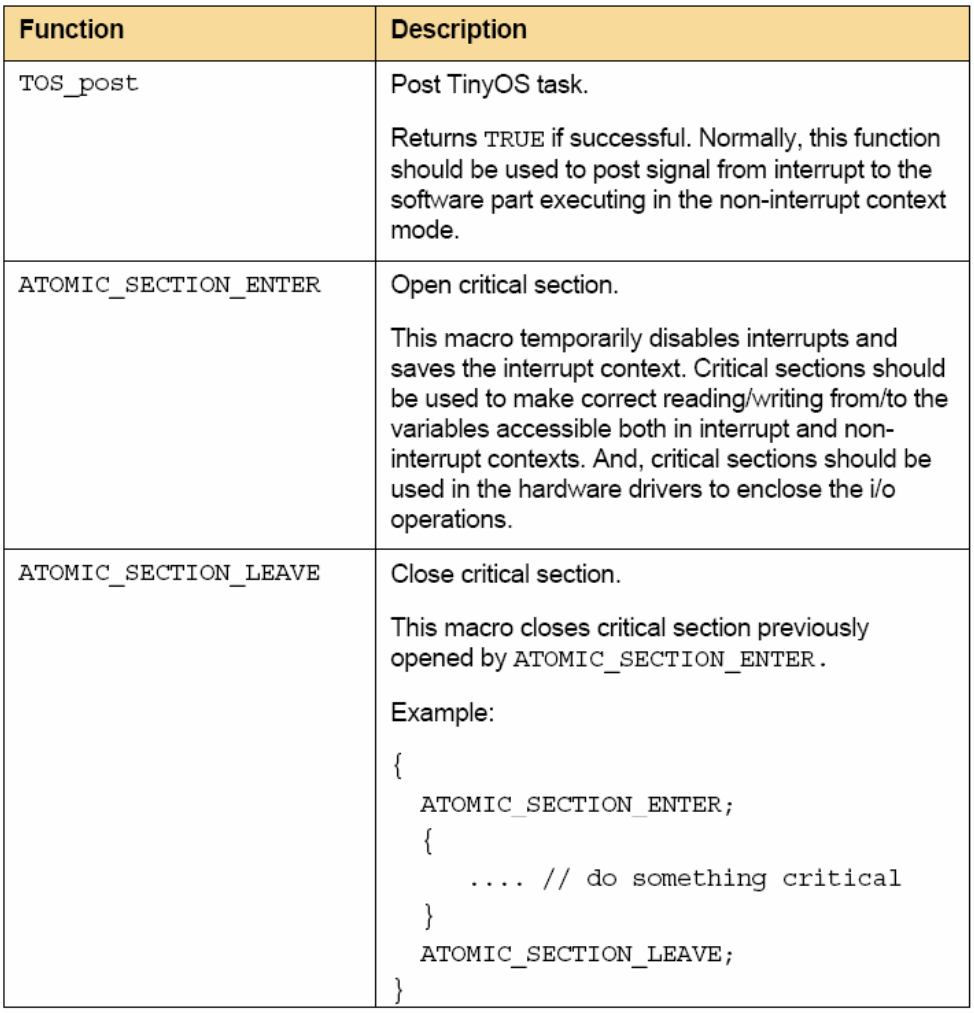
5.3.2 TinyOS Functions

TinyOS is an open-source operating system and can be considered, as reported in [Mes06], “a component-based runtime environment designed to provide support for deeply embedded systems which require concurrency intensive operations while constrained by minimal hardware resources”.

eZeeNet API Software uses a small subset of TinyOS functions, the ones that can be called by a user application are shown in the Table 5.2a-b. They include: TinyOS task management, critical section implementation, and global interrupt management.

User’s applications as noted in [Mes06] should not call any other functions of TinyOS.

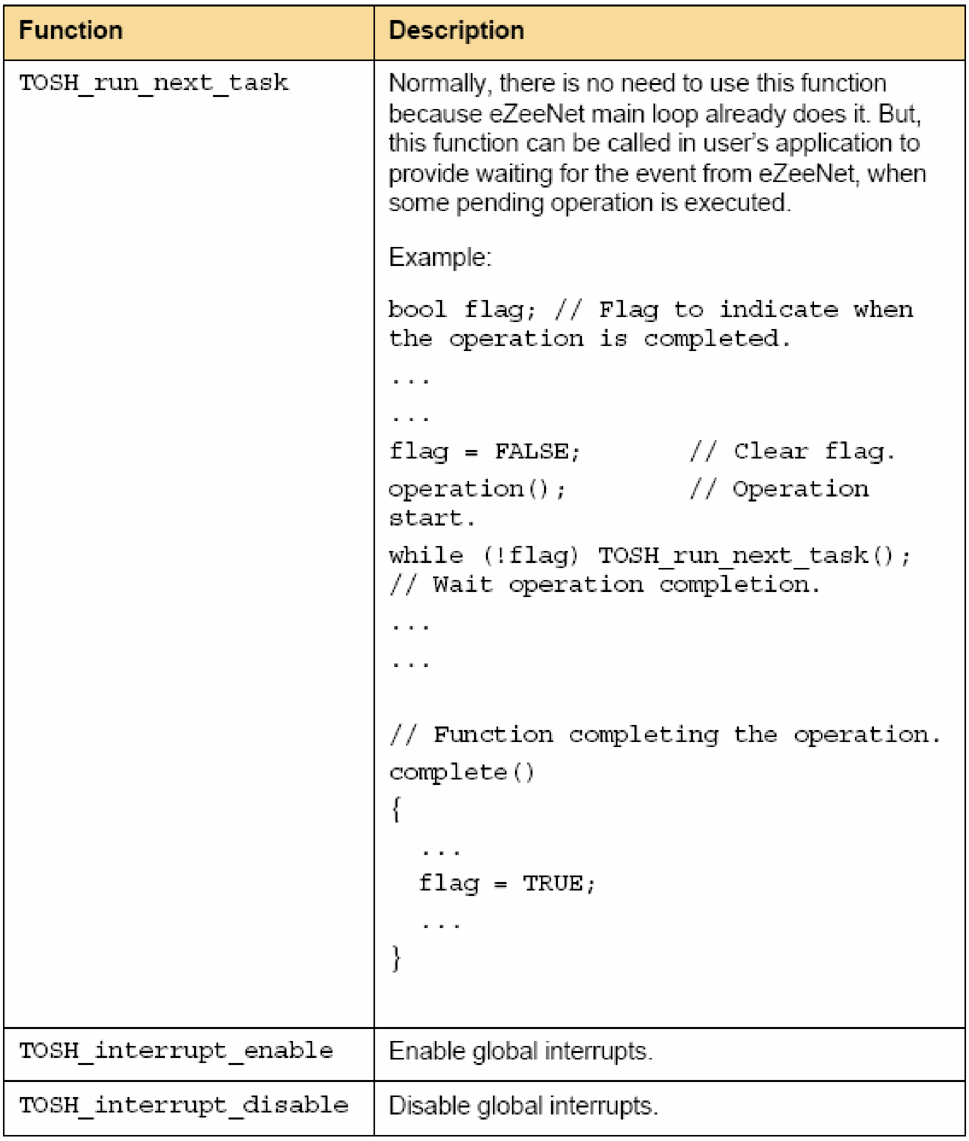
The programming language of TinyOS is C-like that uses a custom compiler 'NesC', but TinyOS functions are C-callable.



Function	Description
`TOS_post`	Post TinyOS task. Returns `TRUE` if successful. Normally, this function should be used to post signal from interrupt to the software part executing in the non-interrupt context mode.
`ATOMIC_SECTION_ENTER`	Open critical section. This macro temporarily disables interrupts and saves the interrupt context. Critical sections should be used to make correct reading/writing from/to the variables accessible both in interrupt and non-interrupt contexts. And, critical sections should be used in the hardware drivers to enclose the i/o operations.

`ATOMIC_SECTION_LEAVE`	Close critical section.
	This macro closes critical section previously opened by `ATOMIC_SECTION_ENTER.`
	Example:
	`{`
	`  ATOMIC_SECTION_ENTER;`
	`  {`
	`      .... // do something critical`
	`  }`
	`  ATOMIC_SECTION_LEAVE;`
	`}`

Table 5.2a - The callable TinyOS functions



Function	Description

`TOSH_run_next_task`	Normally, there is no need to use this function because eZeeNet main loop already does it. But, this function can be called in user's application to provide waiting for the event from eZeeNet, when some pending operation is executed.
	Example:
	`bool flag; // Flag to indicate when the operation is completed.`
	`...`
	`...`
	`flag = FALSE;        // Clear flag.`
	`operation();         // Operation start.`
	`while (!flag) TOSH_run_next_task(); // Wait operation completion.`
	`...`
	`...`
	`// Function completing the operation.`
	`complete()`
	`{`
	`  ...`
	`  flag = TRUE;`
	`  ...`
	`}`

`TOSH_interrupt_enable`	Enable global interrupts.
`TOSH_interrupt_disable`	Disable global interrupts.

Table 5.2b - The callable TinyOS functions

5.3.3 Framework Interfaces

In table 5.3 there is a summary of the main Framework functions and their controlling functionalities.

Function.	**Description**
fw_setUserLoop	Set user's loop
fw_getSystemTime	Get system time

fw_userEntry	Initialize user’s application
fw_warmReset	Warm reset
fw_setParam	Set eZeeNet parameter
fw_getParam	Get eZeeNet parameter
fw_eepromWrite	Direct write to EEPROM
fw_eepromRead	EEPROM direct reading
fw_registerSleep	Register user’s handlers for power management
fw_forceToSleep	Force the node to sleep
fw_appReadyToSleep	Ready-to-sleep indication
fw_forceWakeup	Force the node to wake up

Table 5.3 - Framework functions

These functions supply:

- entry point for user HAL and application initialization
- periodical call for user’s loops
- system time management
- eZeeNet parameters management
- EEPROM management
- periodical calibration of the internal RC oscillator.

The interfaces are declared in the “framework.h” file.

5.4 Development of the application

First of all must be said that our application system must achieve to some basic task before implementing an higher level logic.
For instance each node at startup must read and/or accept its configuration and perform a check on its sensors. When the initialization part is completed the device must search a network to join, it must decide its role and try to join the network. If the network join fails according to its logic and the error received the node will try to switch its role, look up for another network or just set an error status.

When this basic task were achieved then the node may start with the high level logic which basically regulate the measurements gathering rate, the power energy consumption (e.g. via sleep mode) and security (apply encryption)

While operating the devices may also receive, and answer to, unexpected (but not unforeseen) events such as a leave command (due to a parent forced disconnection for example due to the depleted battery energy) or the impossibility to communicate any more with its WSN.

Before describing anything, I should say the developed applications must be considered the main goal that this research was intended to: build an efficient system to gather data on real research scenarios.

As briefly described in the introduction of this thesis the system project was born from a specific need met in a previous research where was built a remote control system for surgical rooms [Gad06] and with an eye to the future researches which the writer himself will be probably personally involved.

The applications developed are of two different typologies: the first one was developed to monitor a house air conditioning plant. The system in this case have, as its main objective, to prove the efficiency and performance declared by the manufacturer of this system and to prove how it can solve many problems such as mould formation because of the walls moisture.

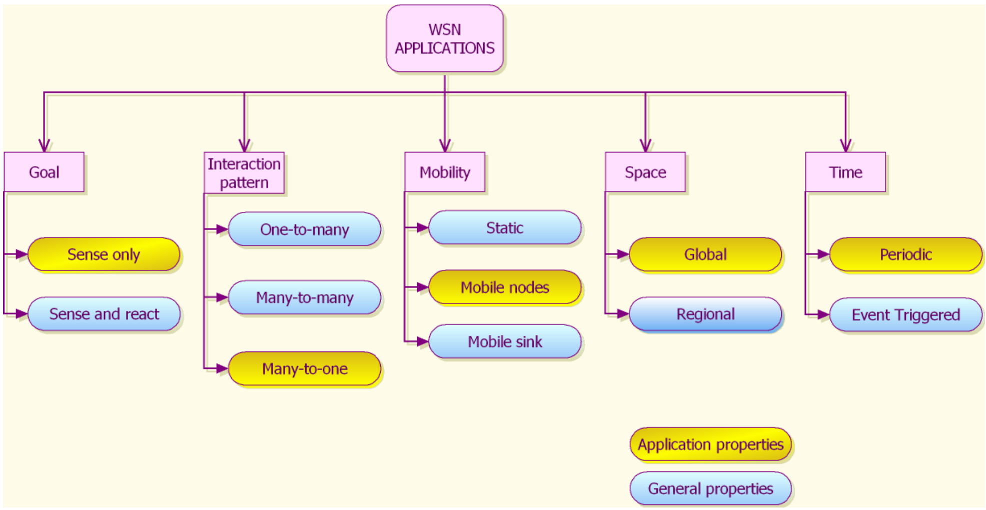


Figure 5.5 –Our application’s taxonomy

This system must be, of course, as non-invasive as possible within an inhabited area and, moreover, it needs to be flexible enough to be moved often and the sensor should be placed in locations such as air conditioning pipes, or bookshelf. Finally the system should disappear from the house inhabitants' sight otherwise it may cause discomfort (for example people may feel observed).

Under such conditions a wireless system is the best choice and the ZigBee wireless sensor network were specifically built for these application field scenarios.

The complete taxonomy's classification for the developed WSN application is illustrated in Figure 5.5.

We can also say that the data flow expected is periodic and non-intensive, because the required values relate on environmental parameter such as temperature, Relative Humidity (RH) and CO_2 that don't change at an high speed rate. For example when each node send its measurements every minute is usually sufficient for most kind of analysis.

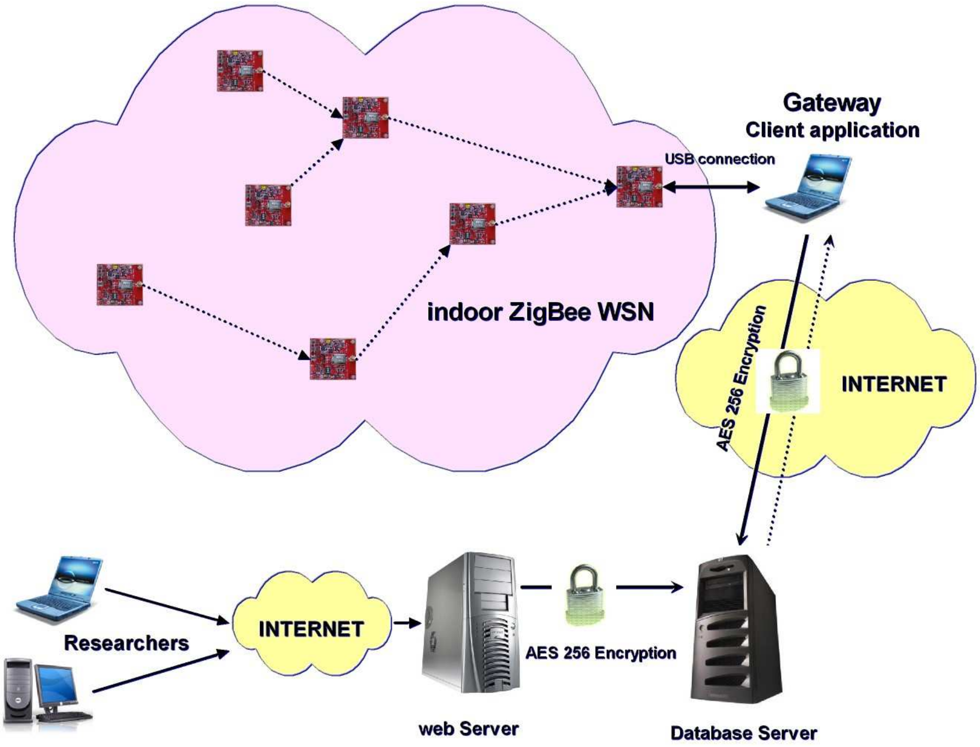


Figure 5.6 –System's architecture

The application is built to suite different application field so that frequently source code addition and restyling will be avoided. The measurement's sample frequency is set by default at one every 5 seconds and can easily be changed via a client command.

The complete system's structure is depicted in Figure 5.6. As can be seen this system requires not only the WSN performing the environmental measurements to be fully operational but also a system which will gather all the data and store it to a database for further analysis.

To Gatherer pc send data immediately to the server using multiple threads, allowing the research to access the values with a very small latency. The latency value is usually less than a second, and without internet line problems is always under the 5 seconds of the default sampling rate thus we can assert the system is working in real time for our purposes.

In this chapter we will focus only on WSN application while in the next chapter will be provided the description for the rest of the system as well as the results of the researches.

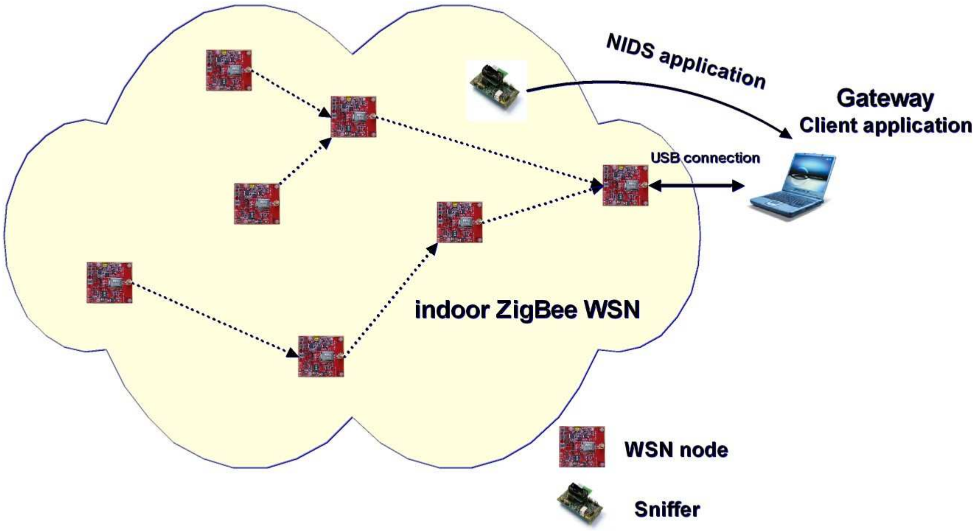


Figure 5.7 –WSN architecture

In Figure 5.7 is depicted the WSN architecture used. The network shape chosen is the tree due to the beacons which allow end-node to have a sleep period between two measurements saving the battery energy. Furthermore the router beacons can be used as an heartbeat by a backup node, as will be explained further in this chapter, without braking the ZigBee standard's rules.

Although a mesh network is more resilient and fault tolerating, the test results supplied does not show a great differences with our system, made of a relatively small number of deployed device (about twenty).

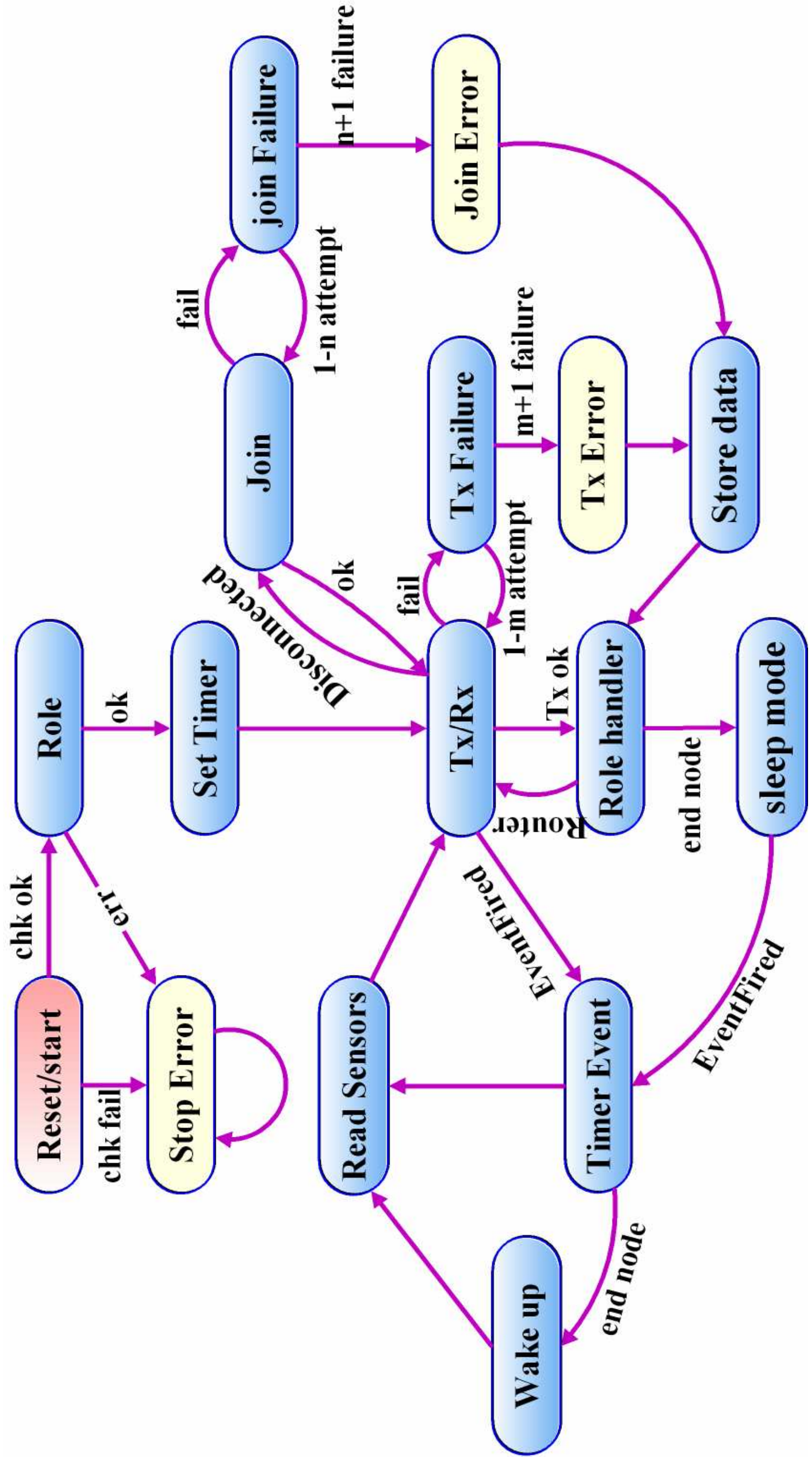


Figure 5.8 –Application functional diagram

The node was introduced to analyze the network's messaging stream helping in the application debugging itself and, more recently, as part of a Network Intrusion Detection System (NIDS)because of the security issues coming up in the literature (see as example [Goo09] and [GoT09]).

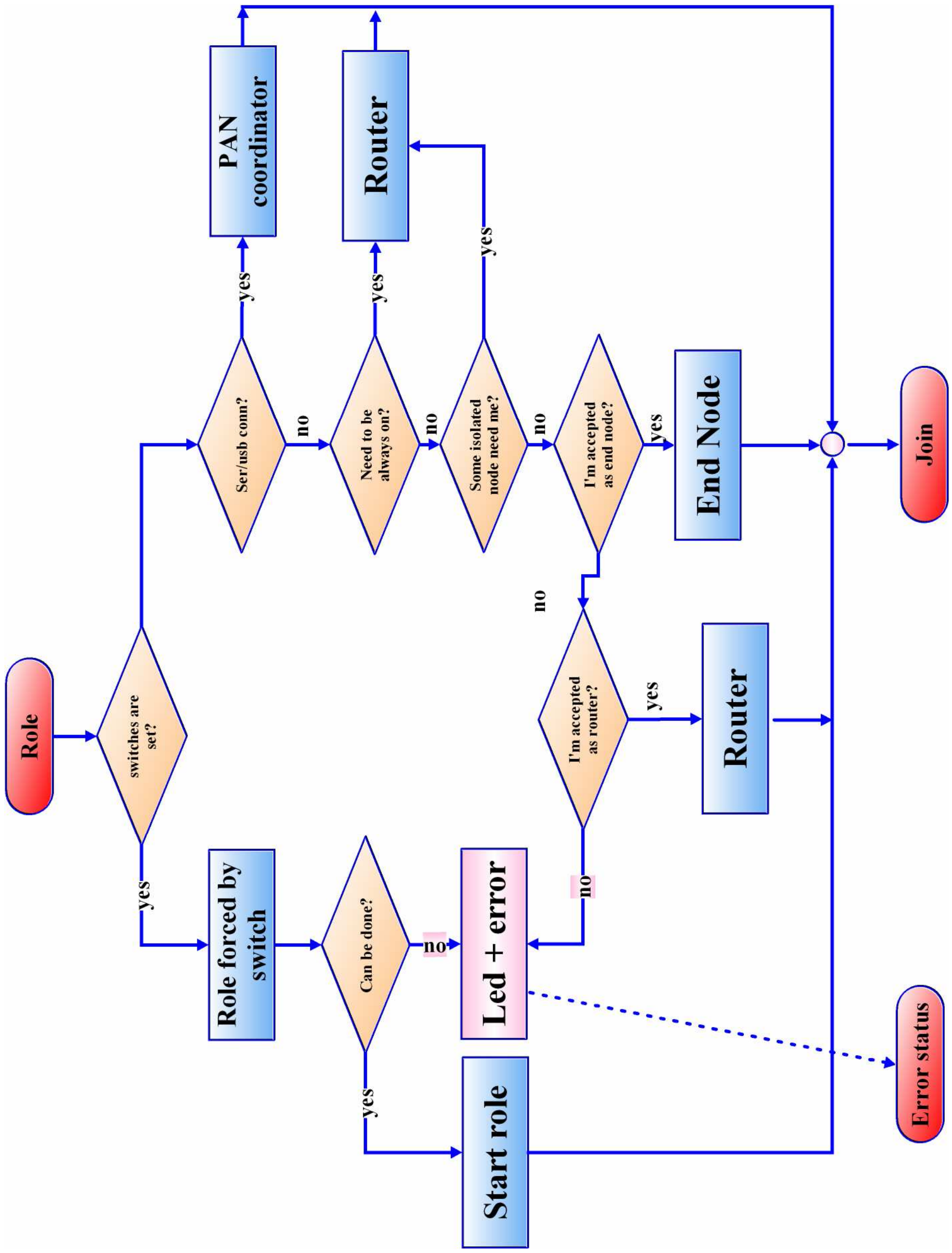


Figure 5.9 –Role decision diagram

The sniffer device was also used to test the flaws and weakness of the wireless Network [PtN98] and [One01]. Many bugs were found, in this way, through the classic buffer overflow attack.

In Figure 5.8 is illustrated the application functional diagram while in Figure 5.9 is shown the simplified version of the role decision algorithm.

The Framework allows a message passing style event, typical of the non-object oriented programming (such as the windows 3.1 event handler) where the main function contains an huge case for all the incoming events and works as a dispatcher.

The following code is the example of the main loop function in the developed application:

```
void mainLoop()
{
//wait for new state can be activated
  if ( ((signed long)(newStateTime - fw_getSystemTime())) >
0) return;
  switch (appState)
  {
    case WSND_INITIAL:
      forceStateWithDelay(WSND_RESET,10000); //watchdog timer
      leds_indication__init();
      leds_indication__indicate(SLEEP);
      checkLocalParams();
      checkButtonsAndParams();
        checkExternalMemory();
        checkSensorList();
      initSensors();
      checkBattery();
        //va controllato il cambio di ruolo anche in base
allo stato delle batterie
      if (isRoleForced())
            checkRole();
        else
            buffer.nodeType = choseRole(); //coordinator WILL
initDataBridge()
      initDataBuffer();
      showRole();
      if (buffer.nodeType = ZIGBEE_COORDINATOR_TYPE)
setNetworkParameters();
      forceState(WSND_START_SEARCH_NETWORK);
      break;

    case WSND_START_SEARCH_NETWORK:
      forceStateWithDelay(WSND_FORCE_RESET,REJOIN_PERIOD);
      leds_indication__indicate(NETWORK_SEARCHING);
      fw_joinNetwork(); //wait join() or lost()
      break;
```

```
//il join setta questo stato
    case WSND_IN_NETWORK_GETSENSORS:
      forceStateWithDelay(WSND_GET_SENSORS_DONE,1500);
      leds_indication__indicate(ACTIVE);
      getBoardSensors();
      break;

    case WSND_GET_SENSORS_DONE:
//sensors has read. sending
      updateDataBuffer();
      if (buffer.nodeType != ZIGBEE_COORDINATOR_TYPE)

forceStateWithDelay(WSND_RESENT_TRY,SUCCESS==sendData(&buffer
,sizeof(buffer))?RESEND_PERIOD:100);
#ifdef WSN_COORDINATOR
      else
//      if (buffer.nodeType == ZIGBEE_COORDINATOR_TYPE)
      {
        leds_indication__indicate(TRANSMIT);
        transmitToDataBridge((void*)&buffer, sizeof(buffer)
); // saves data and transmits through uart
        previousSendTime = fw_getSystemTime();
        forceStateWithDelay(WSND_PREPARE_TO_SLEEP,40);
      }
#endif
      break;
    case WSND_RESENT_TRY:
//additional try to send
            if (myParameters.lastRetryTimes < MAXRETRY )

      forceStateWithDelay(WSND_RESENT_TRY,SUCCESS==sendData(&
buffer,sizeof(buffer))?RESEND_PERIOD:200);
            ELSE
forceStateWithDelay(WSND_RESENT_FAILURE,SUCCESS==sendData(&bu
ffer,sizeof(buffer))?RESEND_PERIOD:200);
      break;
    case WSND_RESENT_FAILURE:
            leds_indication__indicate(LED_WARN_FAILURE);

      forceStateWithDelay(WSND_LEAVE,SUCCESS==sendData(&buffe
r,sizeof(buffer))?RESEND_PERIOD:400);
      break;
//if it is an end device start to sleep,
    case WSND_PREPARE_TO_SLEEP:
//send was succesfull
      forceState(WSND_DATA_DELAY);
#ifdef WSN_ENDDEVICE
//end device goes to sleep
      if (buffer.nodeType == ZIGBEE_END_DEVICE_TYPE)
```

```
   {
      stopSensors(myParameters.sensorList);

forceStateWithDelay(WSND_DATA_DELAY,myParameters.sleeptime);

    fw_forceToSleep();
   }
#endif
   break;
//delay state. Router will do this code while its delay is
not expired
//end device go out from this state immediately after sleep
  case WSND_DATA_DELAY:
   if ((fw_getSystemTime() - previousSendTime) >
ROUTER_SEND_PERIOD)
    forceStateWithDelay(WSND_IN_NETWORK_GETSENSORS,1);
   break;
  case WSND_LEAVE:
   fw_leaveNetwork();
   forceStateWithDelay(WSND_RESET,MAX_LEAVE_TIME);
   break;
  case WSND_FORCE_RESET:
  case WSND_RESET:
   fw_warmReset(FALSE);
   break;
  case WSND_SET_CHANNEL_MASK_DONE:
   {
    static uint16_t ledsCounter;

leds_indication__indicate((ledsCounter++&2)?TURNOFF_ALL_LEDS:
TURNON_ALL_LEDS);
    if
(ledsCounter>=(SET_CHANNEL_MASK_WAIT_TIME/MAINLOOP_PERIOD))
     forceState(WSND_LEAVE);
   }
  case WSND_COMMAND_RECEIVED:
   RESET = processCommand();
    if (RESET) fw_warmReset(TRUE); //o in alternativa
usare il watchdog timer
   break;
  default:
   break;
 }
}
```

All the nodes, except for the coordinator that can also send messages via the usb connection, use the three leds installed on board to show the status.
The message specification is shown in the table 5.4.

The check for any isolated or dead node is not done by the network itself, because it requires the coordinator to use memory and calculation resources which depend directly to the number of attached nodes. This task is instead performed by the gateway application that connects the PAN coordinator to the rest of the world. The gateway application will be briefly illustrated in the next chapter, but it is obvious that its main tasks are the data gathering, their validation and data forwarding to the database server (or the temporary local storage if the connection to the DB server cannot be performed).

The Gateway application, running on a personal computer has much more resources and it can easily maintain a node table via one of the threads without missing the main tasks just listed.

Node state	**LED state**		
	LED1 Red	**LED2 Yellow**	**LED3 Green**
Sleeping (end device only)	OFF	OFF	OFF
Network searching			blinking
Having joined the network			ON
Message receiving		blinking	ON
Message transmitting	blinking		ON
Too many send failure		blinking	OFF
Buffer full	blinking	blinking	OFF/ON
Changing channel mask	blinking	blinking	blinking

Table 5.4 – Application LED indication

5.4.1 Call Sequences

When the application start due to a power on event or a cold reset, it will start an initialization phase to properly configure the framework and the application parameters and to set the hardware accordingly. The program initialization sequence is shown in Figure 5.10.

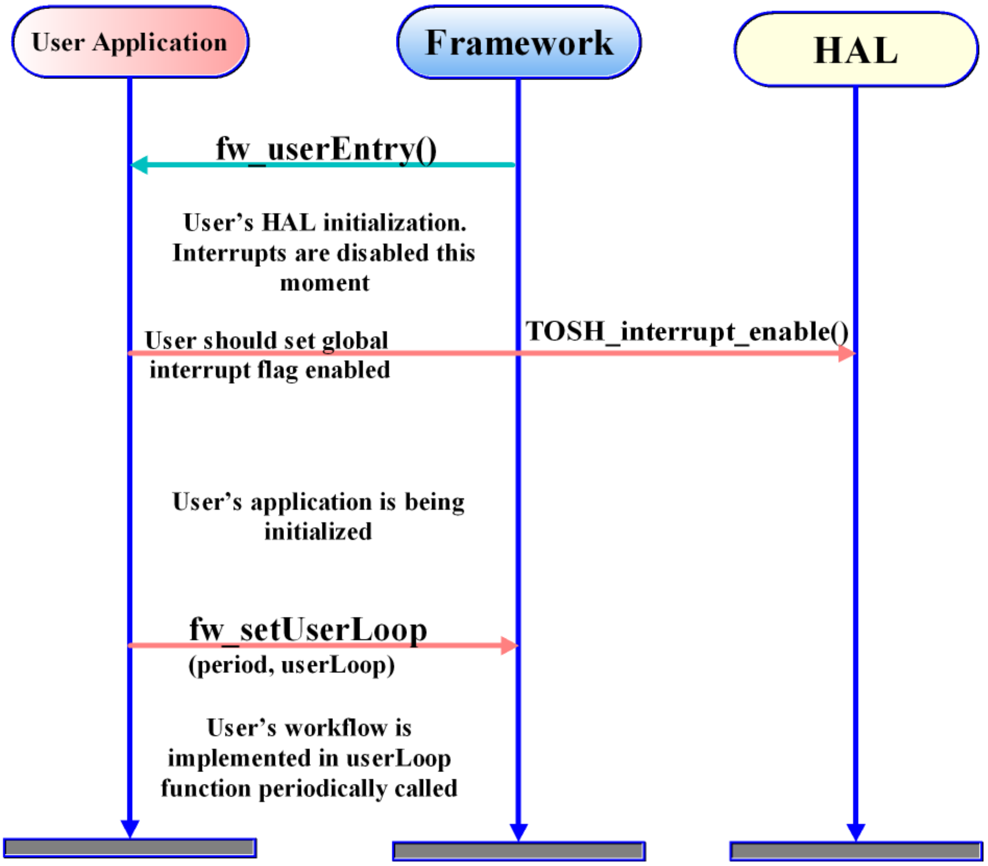

User Application
Framework
HAL
fw_userEntry()
User's HAL initialization. Interrupts are disabled this moment
TOSH_interrupt_enable()
User should set global interrupt flag enabled
User's application is being initialized
fw_setUserLoop (period, userLoop)
User's workflow is implemented in userLoop function periodically called

Figure 5.10 - Application initialization sequence

The *fw_userEntry()* initializes user's HAL and application and it should be implemented in user's code. initialization. After the initialization phase the interrupt can be enabled and must be called the fw_setUserLoop(period, userLoop) function which allows to set parameters of user's handler . The period is expressed in milliseconds and the userLoop parameter is a pointer to a void function.

To reduce the power consumption the device can be set to go into the sleep mode.

The sleep mode activation sequences are illustrated in Figure 5.11 and 5.12. The procedure can be initiated both by the framework (fig. 5.11) or by the application itself (fig. 5.12).

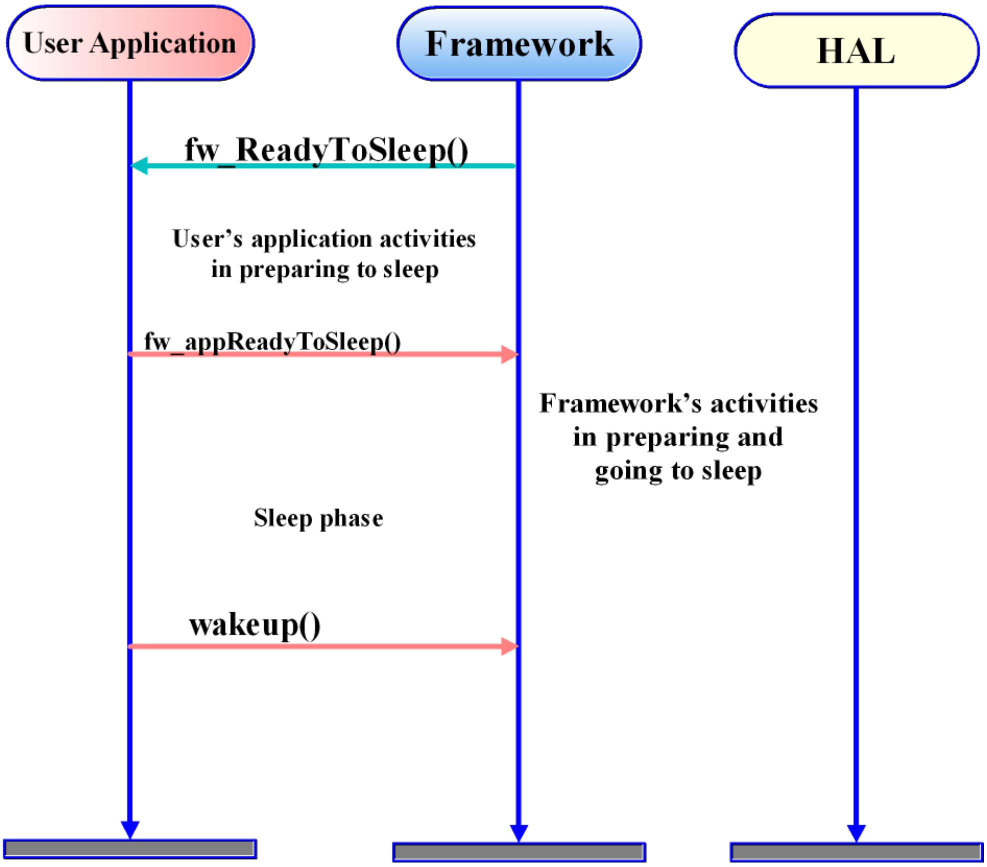

User Application
Framework
HAL
fw_ReadyToSleep()
User's application activities in preparing to sleep
fw_appReadyToSleep()
Framework's activities in preparing and going to sleep
Sleep phase
wakeup()

Figure 5.11 - Going to sleep sequence (when initiated by Framework)

The Framework initiated sleep mode seems to affect the application event timer which usually reduces its period before it fires the event. More information about this misbehaviour will be done in "on field analysis" section further in this chapter.

As can be seen from the two sequences the mainly difference between a framework initiated sequence and the user's application sequence is merely the user call to invoke the framework *fw_ForceToSleep()* function.

On the other hand these differences affect the application flow allowing the developer to choose the actions performed between two sleep phases, such as reading sensors data and store/send them as well as enable/disable the watchdog timer.

For example the data compression, developed by the user and requiring a 'long time' period to be performed, cannot be done between the *fw_ReadyToSleep()*and the *fw_appReadyToSleep()* calls due to application crash probably caused by a to-early forced sleep status.

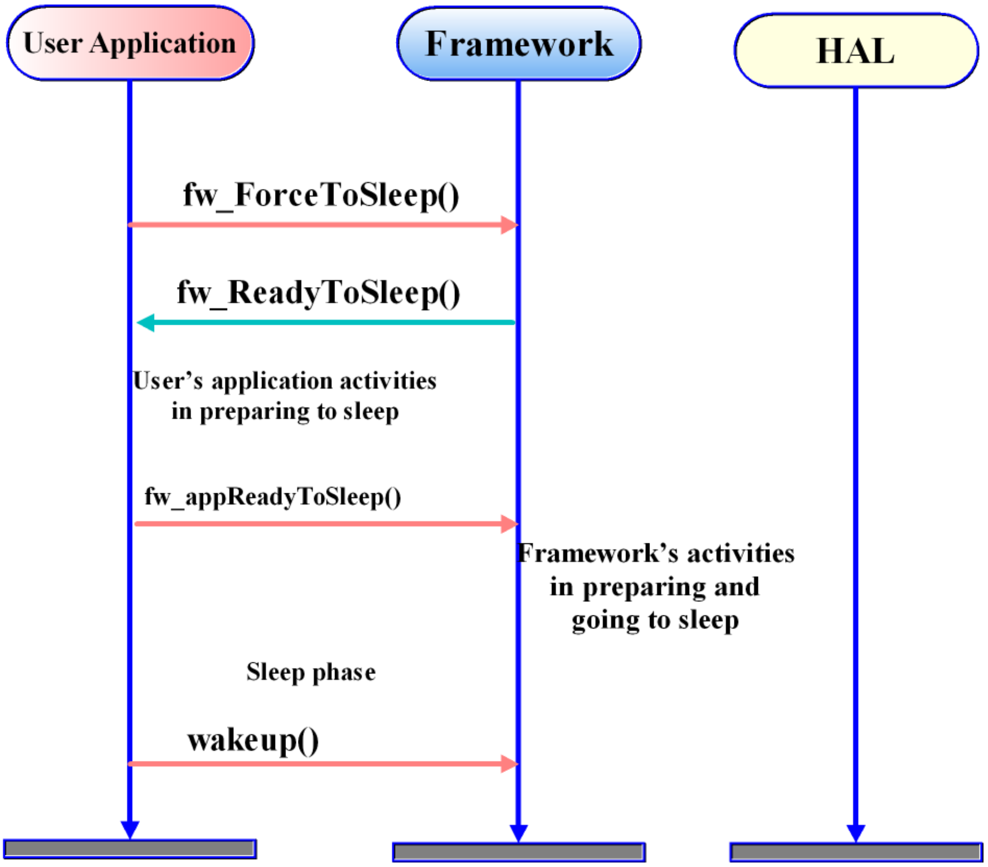


Figure 5.12 - Going to sleep sequence (when initiated by user's application)

the waking-up sequence initiated by user's interrupt handler during sleep is shown in Figure 5.13.

In this sequence the HAL receives, from any attached device or from the timer, an interrupt event and invokes the user interrupt handler which provides, based on the event answer to the call's interruption.

During the interrupt event, any incoming command message will be stored to a command message buffer, mainly because all activity, including command execution such as network leave and role change must be done only when the device is fully operational.

After the interrupt phase is completed, the application can start the wakeup procedure calling the *fw_forceWakeup()* framework's primitive and the device will be fully operative again ready to perform all the required measurements.

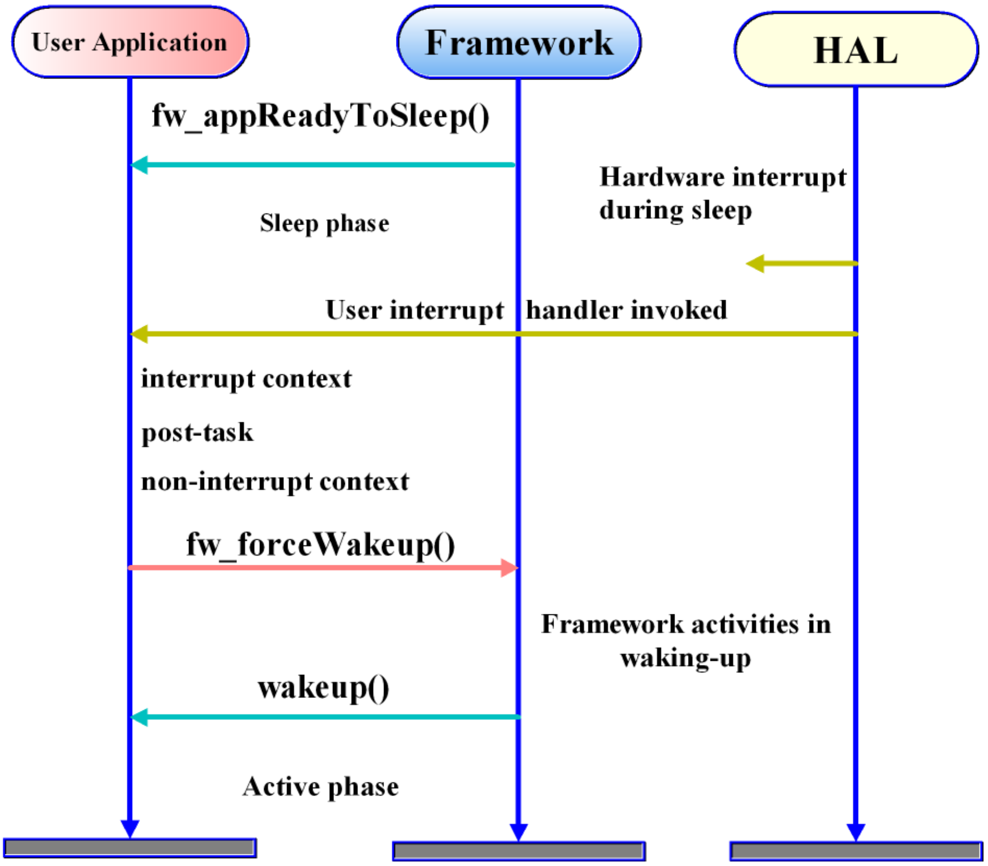


Figure 5.13 - Waking-up sequence, when initiated by user's interrupt handler during sleep

The connection sequence, illustrated in Figure 5.14 can be fully supplied by Framework itself relieving the user's application developer from the burden of controlling the network connection.

In this way, however, the device network role (PAN coordinator, router, end-point) is selected by switches and not changeable.

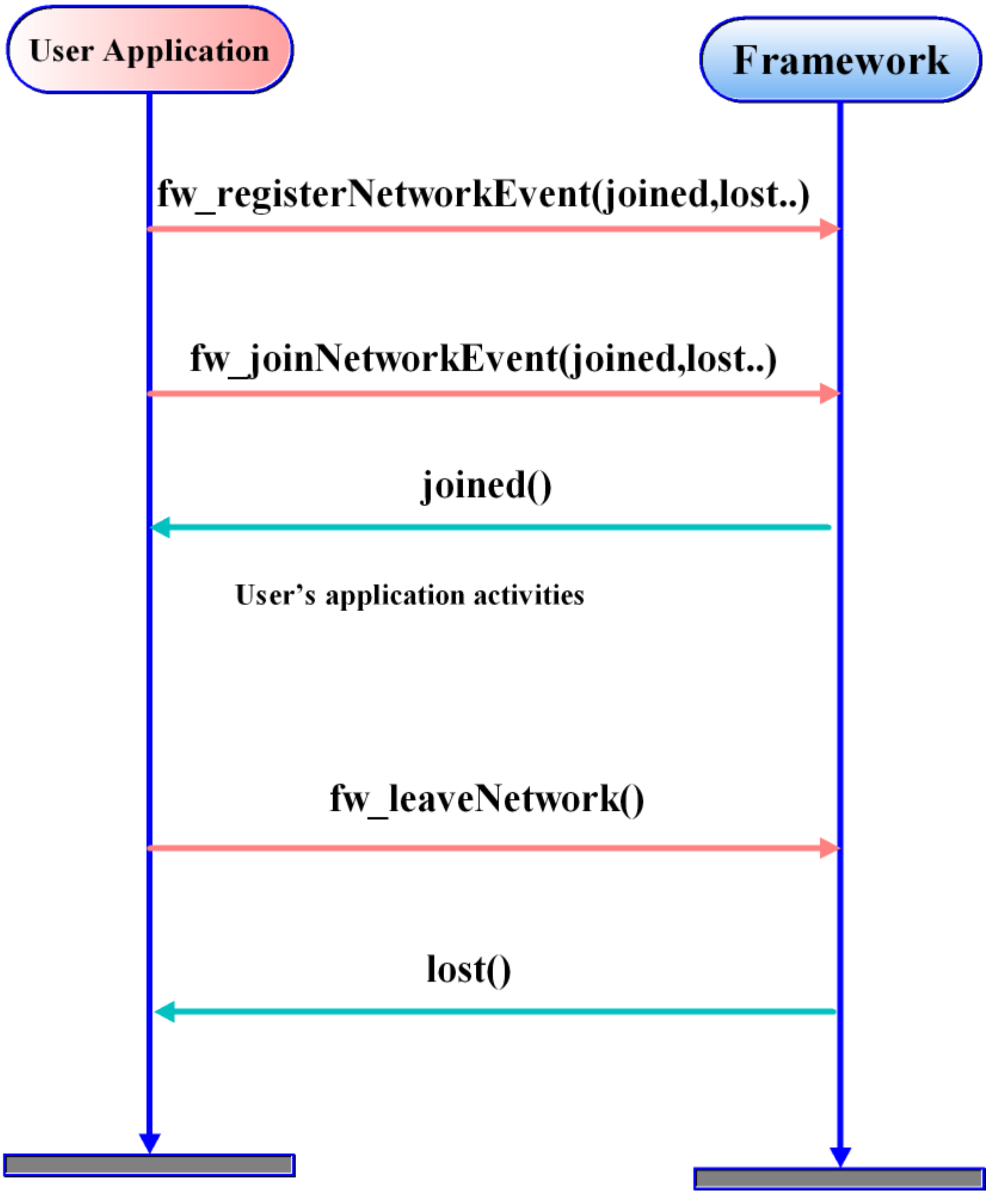

User Application
Framework
fw_registerNetworkEvent(joined,lost..)
fw_joinNetworkEvent(joined,lost..)
joined()
User's application activities
fw_leaveNetwork()
lost()

Figure 5.14 - Join-leave sequence

Since a fully dynamic network which adapts the node's role depending on situation is much more advisable and resilient, the join/leave procedure in the actual developed application is controlled by the application itself, invoking when necessary the Framework primitives.
The general join-leave-join sequence is shown in Figure 5.15.

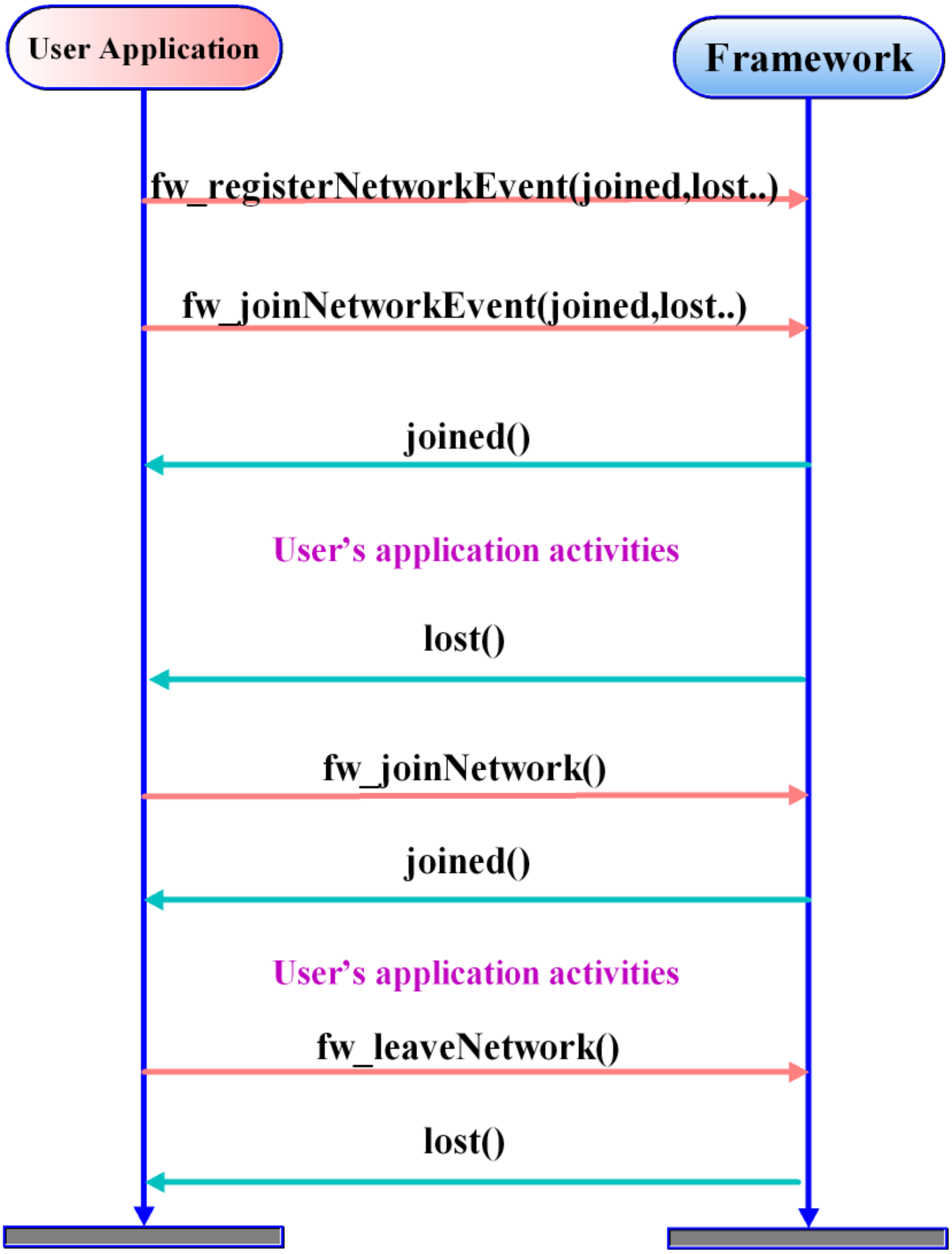

User Application
Framework
fw_registerNetworkEvent(joined,lost..)
fw_joinNetworkEvent(joined,lost..)
joined()
User's application activities
lost()
fw_joinNetwork()
joined()
User's application activities
fw_leaveNetwork()
lost()

Figure 5.15 - Join-lost-join sequence (automatic networking disabled)

5.4.2 The heartbeat system

When the WSN application was tested in an on research's field one of the main problems was the node 'disappearing', meaning that suddenly a random node stop working for a variable period of time. Such behavior was unpredictable and could happens after few minutes or days. A continuous node check process by the PAN coordinator was out of discussion because of the required resources' cost (this control was implemented in the gateway application).

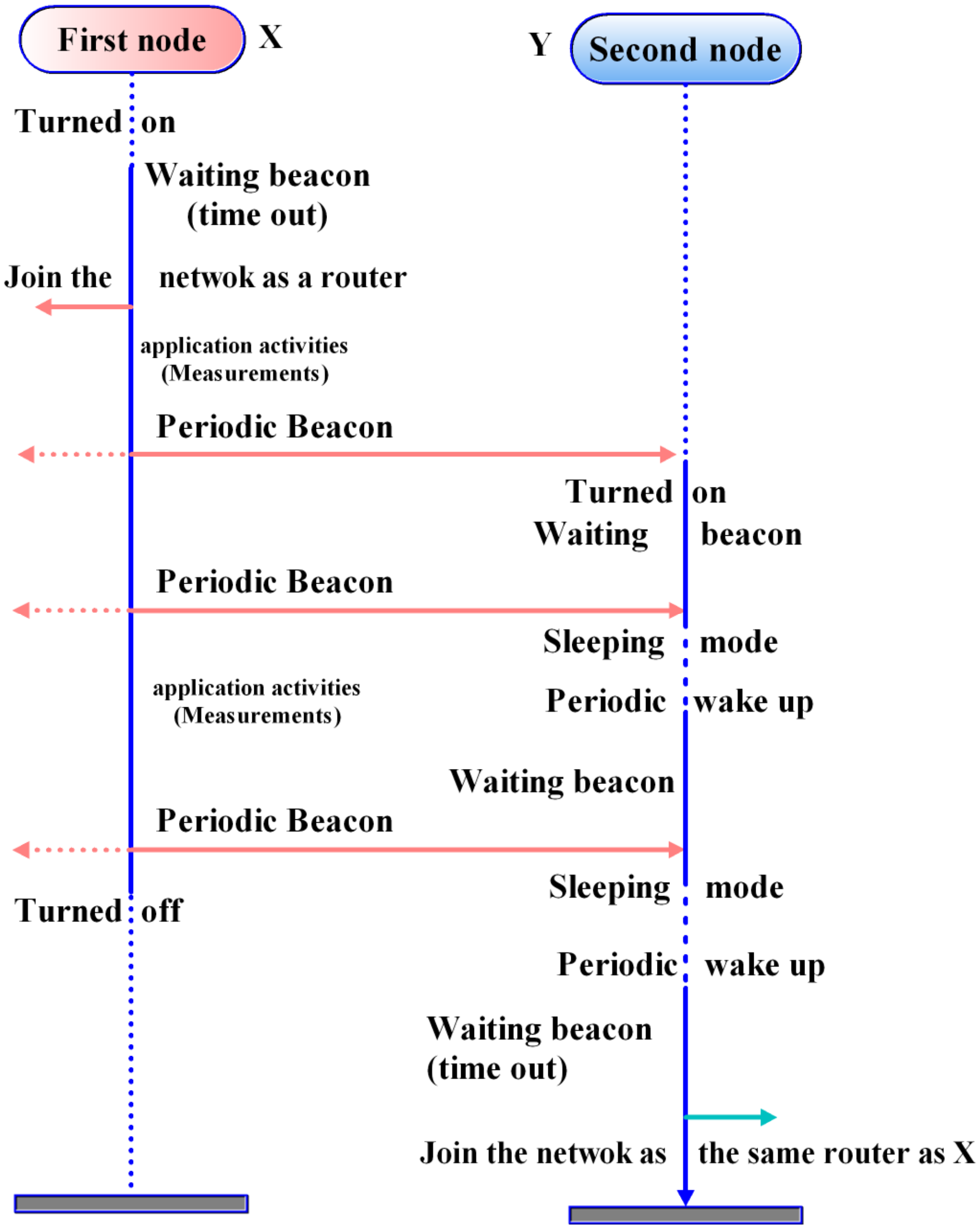


Figure 5.16 - Heartbeat system between two nodes (tree topology)

There are several reasons of these nodes disappearing behavior such as strong signal interferences, application or ZigBee stack crash (without watchdog intervention).The problems were only partially solved in the thesis period due to the manufacturer ZigBee stack update, a re-codification of some critical application functions such as sensor reading and I^2C memory management.

One of the most efficient methods to solve the problem was forcing a cold restart after each sensor read cycle this take usually about 2 seconds (0,5 sec for the startup process and 1,5 or more for configuration and join the network again).

However the restart can be done only by end-node device with non-continuous sensor reading and it does not eliminate completely the problem.

To solve this problem affecting very important measurement the application developed includes an heartbeat system which involves two nodes that share the same address.

This system is illustrated in many works (see [Tan02]) as a couple of computer acting as servers machine. One of the computer provides the services required by the clients and sends a heartbeat message to the second computer that is just waiting. When the first computer stop sending the message (as an heartbeat signal suggest it usually means a severe malfunction of the computer itself) the second computer starts and takes the place of the first computer acting exactly as it is the same computer.

The originality of the solution is the extension of this idea to a wireless context taking advantage of the beacons signals sent by routers (in a tree topology). This also means that we don’t need to modify the ZigBee standard to add this feature.

As we can see from figure 5.11 when one of the node Y start, before trying to join the network, it waits for a beacon message of the other device (node X). If the main node is working, the backup node (Y) works as a end-node with sleep periods, if Y does not receive the beacon signal it joins the network acting as exactly as the X node. The sleeping period it’s programmable and reflects the ‘response time’ of the heartbeat system: If Y sleeps for 5 seconds it will backup the X node died in about 5 seconds, during this period the data will be lost.

Moreover there are three conditions to satisfy to keep the heartbeat system working (without breaking the ZigBee rules):

- The network must use implement tree topology (mesh topology does not allow beacons)
- the X device must act as a router, since only the routers, in a tree topology send beacons

- The two nodes must be in the direct range because the second node must receive the beacons directly (this usually is not a problem as the two nodes must measure the same event)

As alternative solution the two nodes must work together, but in this case they waste their power energy in performing the same measurements.

5.5 Buffering

When the accelerometer was introduced the bandwidth requirements increased since the node needed to send at least eight packet per second, but with a beacons every 0,25 seconds (see par 4.5.1) the number of messages sent could not be more than four. Moreover as already mentioned (and discussed further in paragraph 4.9) sometimes the nodes could not send messages for a variable period of time.

Two solutions were implemented for such nodes. The first one was a RAM buffer for the accelerometer data in this way even if prolonged network's absence happens due to, for example, signal interferences, the device can continue to achieve its task storing the measurement into the memory.

When the device can re join the network it will start sending all the stored values.

The second solution was data compression which helps to reduce the number of packets saving also the battery energy and decreasing the bandwidth needs. Data compression will be discussed in the next chapter (see 4.8).

The following algorithm briefly describes the data buffer management:

```
Read values(LastMessage)
If connected
     While (ObjectList is Not empty)
          send Next(packet)
     Send LastMessage
     //it's in a different buffer area
Else
     If FRAM Memory present
          If AddObjectToList(LastMessage,Time)
          Else set leds (Buffer Full)
/*the values are not discarded but the next read
will overwrite them*/
```

The data buffer is implemented as a circular list stored in an array with a start and an end pointer, using the typical list functions (such as ListEmpty, push, pop, ListFull).

When the buffer was implemented were available as I2C flash memory the module 1 Megabit chip is available Ferroelectric Non-volatile RAM (FRAM). This module has great advantages versus the standard flash memory, first of all the read/writes cycles are about 10^{14} times meaning the chip use is virtually unlimited, much more than the typical 100.000 cycles of the flash RAM. Additionally FRAM has better read/write performance (400 khz clock) and lower power consumption (Active Current < 150 μA, 90 μA Standby, 5 μA Sleep Mode versus a 2mA of a flash eeprom)

This buffer area provides a storage space for about 4 minutes of measurements (considering 90 values of 16 bits per second) which is enough for the most disconnection problems.

5.6 Data compression

The ZigBee WSN are basically made for low traffic rate application. Additionally the used WSN has a clear bottleneck in the PAN coordinator connected to the Gateway computer via an USB port installed as a virtual serial port. This bottleneck is very common with this second generation device (is expected to be solved in the nowadays third generation).

To improve the total bandwidth available one of the best solution found was the data compression.

Since we are compressing measurements we need certainty that we achieve the same what we compressed after decompression, thus lossless compression is the only choice. The compression algorithm chosen is the Hoffman coding due to its compression performance and its simple algorithm. The WSN device implementation of this code use a static table to eliminate the computing and memory resource needed by the modeling phase of the compression system. The results will be a worse (i.e. a bigger size of the compressed data) than we can expect adopting also a modeling phase based on the data flow itself but don't require additional resource besides the pre-calculated table.

For more information about this compression algorithm see appendix C.

5.6.1 Data structure

After the Huffman tree creation (see appendix C) as the figure C.1 shows each leaf block has a given weight. The largest-numbered node in a block is the leader of the block. The main operations supported by the data structure are [Kun85]:

- Represent a binary Huffman tree with nonnegative weights that maintains the invariant.
- Store a contiguous list of internal tree nodes in non decreasing order by weight; nodes of the same weight are ordered respect to their numbering.
- Find the leader block based upon the numbering.
- Contents interchange of two leaves of the same weight.
- Increment the weight of the leader of a block by 1, which can cause the node's numbering to *move* past the implicit numberings of the nodes in the next block, causing their numberings to decrease by 1.
- Represent the correspondence between the k symbols of the alphabet appeared in the message and the positive-weight leaves in the tree.
- Represent the n-k symbols in the alphabet that have not yet appeared in the message by a single leaf 0-node in the Huffman tree.

The components of the data structure are listed below. The number of leaves of zero weight is specified by integer variables M, E, and R:

$$M = n - k = \text{the number of zero-weight symbols in the alphabet}$$
$$= 2^E + R, \text{ where } 0 \leq R < 2^E, \text{ except that } R = -1 \text{ when } M = 0.$$

The data structure uses an explicit numbering, which corresponds to the physical storage locations used to store information about the nodes. This must not be confused with the implicit numbering defined in the last point. Unless stated, all references to node numberings are based upon the explicit numbering. Leaf nodes are explicitly numbered 1 to *n* in contiguous locations in physical memory, and internal nodes are explicitly numbered ***n+max{1, M}, ... , 2n-1*** in contiguous locations in memory.

The node *q* is a leaf node if and only if **q ≤ n**. When k < n (when M > 0), the 0-node in the Huffman tree is node M, and the positive-weight leaves are nodes M + 1, ... , n.

Nodes 1, ... , M represent letters of zero weight, though only node M actually appears in the Huffman tree. When k > 1 (that is, when M < n), the root of the tree is internal node 2n - 1; otherwise, we have M = n and the root of the tree is node n, the 0-node.

There is a close relationship between the explicit and implicit numberings: For two internal nodes p and q, we have p < q in the explicit numbering if and only if p < q in the implicit numbering; the same holds for two leaf nodes p and q.

The tree data structure is called a “floating tree” [Kun85] because the parent and child pointers for the nodes are not explicitly maintained.

Each block, indeed, has a parent pointer and a *rtChild* pointer that point to the parent and right child of the leader of the block. This allows a node to slide over an entire block without having to update more than a constant number of pointers. The locations of the parents and children nodes in the block can be computed in constant time via an offset calculation, due to the contiguous storage of leaves and of internal nodes, from the block's parent and rtChild pointer.

The correspondence between leaf nodes and the letters they represent is given by the arrays alpha and rep:

Alpha[q] = j, for $1 \leq q \leq n$, $1 \leq j \leq n$, if and only if a_j is the symbol represented by node q.

Rep[j] = q, for $1 \leq j \leq n$, $1 \leq q \leq n$, if and only if node q corresponds to letter $a_{j.}$

The main entity in the floating tree representation is the block. Blocks are numbered in the range 1, ... , 2n - 1 in no particular order. Mapping between blocks and nodes is given by

block[q] = block number of node *q*, for $\max\{1, M\} \leq q \leq n$ or $n + \max\{1, M\} < q \leq 2n - 1$.

The next eight arrays of integers are each indexed by a block number *b* in the range $1 < b < 2n - 1$:

weight [b] = weight of each node in block b.

parent [b] = the parent node of the leader of block b, if it exists; and 0 otherwise.

parity [b] = 0 if the leader of block b is a left child or the root of the Huffman tree; 1 otherwise.

rtChild[b] = q if b is a block of internal nodes and node q is the right child of the leader of block b.

first[b] = q if node q is the leader of block b.

last[b] = q if node q is smallest-numbered node in block b.

prevBlock [b] = previous block on the circularly-linked list of blocks.
nextBlock[b] = next block on the circularly-linked list of blocks.

Each slot in the array *weight* must be capable of storing any integer in the range [0,t]. The unused blocks are linked together using *nextBlock* in a list headed by

availBlock = first block in the available-block list if the list is non-empty; and 0 otherwise
The final component of the data structure is an array indexed by $1 \leq i \leq n$:
stack[i] = ith-to-last bit of the encoding of the current letter being processed.

Except for the elements of the array weight, each integer variable can take on at most n or 2n - 1 values, which requires either ($\log_2 n$) or ($\log_2 n$) + 1 bits of storage. The total amount of storage (in bits) needed for the data structure is

$$2(\log_2 n) +[(\log_2 \log_2 n) + 2n(\log_2 n) + (2n-1) [(\log_2 t) + +7 (\log_2 n) 7] + (\log_2 n)+ n \approx \mathbf{16 (\log_2 n) + 15n +2n [\log_2 t]}$$

The storage requirement can be reduced by n($\log_2$ n) bits if separate available-block lists are kept for internal nodes and leaf nodes, since leaf blocks do not need a rtChild value. If storage is dynamically allocated, instead of a pre-allocated array, it will be much less.
In our case if we consider n = 256 (8bit symbols) and t = 16bit integer the storage required (a pre-allocated array for performance and memory management reason) is about 12 Kb.

5.6.2 Data compression validation

When compressing data one of the biggest problem is that one bit error in the package can waste all data decompression process.
Thus when the data compression is applied the application calculate also CRC16 value to ensure data validation
The byte-oriented CRC algorithm is quite simple:

```
while message not exhausted
     calculate control byte from R’s top byte
     X ← sum of CRC at various offsets that are to
          be ⊕-ed into R in accordance with
          the control byte
```

```
      shift R left one byte
      read new input byte into rightmost byte of R
      $R \leftarrow R \oplus X$
```

Is to note that most of the calculation can be pre-computed, so a more efficient implementation will use a pre-calculated table

```
while augmented message not exhausted
      idx ← leftmost byte of R
      shift R left by one byte
      read in a new input byte
      use idx to index table of 256 16-bit values (32 bits for CRC 32)
      $R \leftarrow R \oplus$ table value
```

The following code use a pre calculated table CRC algorithm

```
u_long table[256];
u_long crc16(u_char *buf, int len) {
      u_char *p;
      u_long crc;
      if (!crc16_table[1]) init_crc16(); //must be created
      crc = 0xffffffff;
      for (p = buf; len > 0; ++p, --len)
            crc = (crc << 8) ^ table[(crc >> 24) ^ *p];
      return ~crc; /* return the complement */
}
```

In our WSN application the table is stored in the program itself and does not need any further initialization code.

5.6.3 Compression results

The modelling stage can be a resource and time computing greedy task to be performed by a 4 Mhz (and 4 Mips) device doing several other operation such as wireless network listen/transmit, and sensors’ measurements.
Instead, as a compromise, we can pre calculate the Hoffman symbols table and then implement on the node only the coding stage. This was the solution developed for the WSN system.

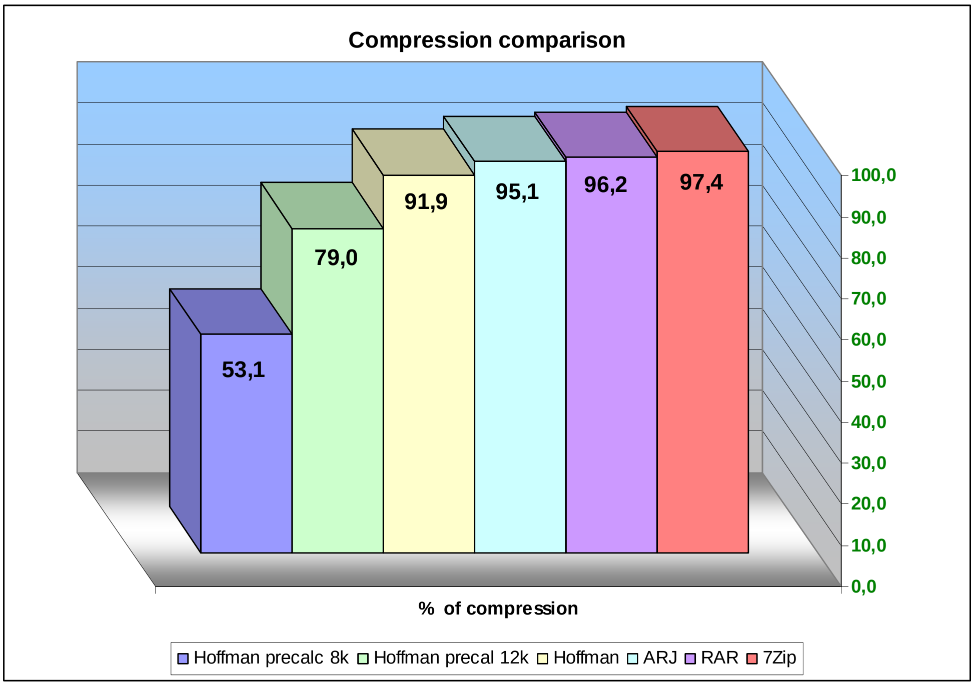


Figure 5.17 - The device data compression rate comparison

The Hoffman compression algorithm was chosen just because of its lightweight and speediness of the coding stage.

We are aware that the solution is non optimized on the real data flow and we expect a final compression rate far less than the one obtained analyzing the data flow itself. To reach a better result, the pre calculated table was built upon a sample dataflow coming from the same sensor connected to the device. The final results are shown in figure 5.17, the first to left bar are the compression rates coming reached by the node with respectively $t=2^8$ and $t=2^{16}$ (see appendix C).

5.6.4 The software analysis

In complexion we can say the ZigBee stack proved to be a real work-saving library removing most of the from time needed for design and developing of the network. However the stack was also create to ease the hardware programming, deleting the need for the Application developer to know the device architecture and this task is not achieved at all. It's true that developer does not need to know how the boards itself is built but when a sensor must be changed/modified like in our situation, the lack of standards force the developer to a machine-level programming accessing the MCU pins directly to read/write information, for example the sensirion sht75

Temperature/RH sensor does not use the I^2C bus but a similar proprietary two-wired bus.

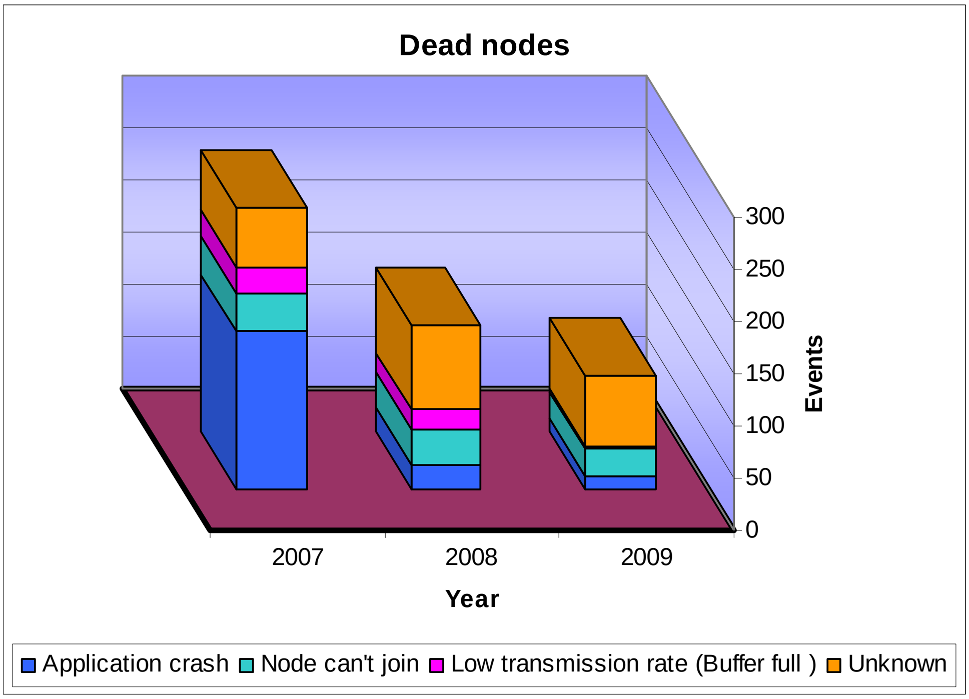


Figure 5.18 – Number of dead nodes

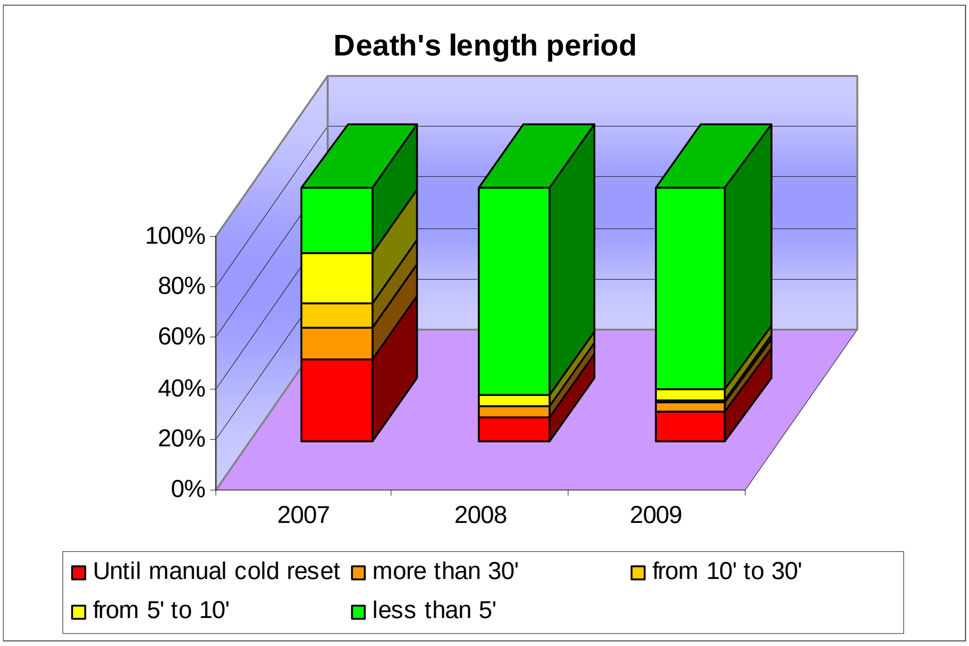


Figure 5.19 – Node's death period (green is better)

The stack itself suffers from the typical software youth problems.
The automatic Framework’s behaviour such as going to sleep, join, leave, transmit data seems to affect the event timer which usually fires the event within a reduced period of time. For example if you set the timer on 5000ms to read temperature (and send it) the event will be initiated every 1500ms instead.
This period cannot be increased unless the application is developed without using the automatic behaviour.
Another example, involving the data compression, developed by the user and requiring a ‘long time’ period to be performed, this compression cannot be done between the *fw_ReadyToSleep()*and the *fw_appReadyToSleep()* calls due to application crash probably caused by a too-early forced sleep status.
Moreover the use of TinyOS calls such as *TOSH_run_next_task()* and atomic blocks are not very clear in the kit documentation. And if the first next_task call is easy to use (and used and very often), once understood its meaning the next code showing the atomic blocks examples may be not clear enough.

```
ATOMIC_SECTION_ENTER
    battery__state = IDLE;
    adc_close( ADC_BAT );
ATOMIC_SECTION_LEAVE
```

In this first example is easy to understand that the two operation are tied together. The next one is:

```
ATOMIC_SECTION_ENTER
      Sht75__state = IDLE;
ATOMIC_SECTION_LEAVE
```

This one is a little obscure, usually it’s not needed for any variable to have an atomic block when it is assigned a new value. But without the atomic section this operation can fail with unbelievable and unexpected results.
Another negative aspects found in the stack architecture was the lack of control about the buffer overflows. Using the sniffer board were generated fake oversized messages and we obtained several application crashes. In the same way, also a non-listed (fake) command message gives unpredictable results.
Finally we can consider the code size of the developed application. The available memory (see paragraph 5.3.1) is not much, but we must consider that we have an entire ZigBee stack loaded.

The new ZigBee versions implemented by the manufacturer, with more and interesting specifications, decrease this free memory value to much to be considered safe the application porting to the new stack.

Section	Max size	Used size
Code	96kb	≈78kb: • 37 kb base code • 6 kb AES+ AES start Key • 8 kb Compression algorithm • 12 kb Pre-calculated compression table • 15 kb sensor drivers
Data	6kb	< 1 kb data structures 2 kb area for AES 2 kb area for compression
Stack	1kb	< 1 kb

Table 5.5 – Actual code size

The porting must wait the third generation MCU and boards.
In table 5.6 is briefly reported the main problems found and solved.

Problem	How is solved	Note
USB virtual com at 38400 baud	Serial flow control applied requiring a reconnection every time a corrupted packet is received	It works only at 57600 baud, and the resync lose part of the performance
Node Battery charge depleted in less than 2 days	Sleep/wakeup for the sensors applied by application and tree structure	Node now can work for 1 week (router) and about 3 weeks (end node)
Timer fired before the requested period	Application force the sleep/wakeup disabling the framework sleep/wakeup automatic behaviour	The new framework release seems to have partially solved the problem
Temperature sensor is	Use a better sensor	The sensor can be

near the voltage regulator (VR) ad its measurements are sometimes greatly affected by the VR heat	(Sensirion) with a small wire	inserted in small space without involving directly the board
The node cannot be inserted in the air flow pipe due to temperature and/or moisture	Used sensor (Sensirion) with a small wire (only the sensor is inserted into the air flow pipe)	The node stop working completely at -2°C and a condensing humidity my be very dangerous to it
Security flaws found also in implemented AES	AES implemented with primary key into code space, AES replay disabled to avoid replay attack, Nonce introduced	Also implemented a simple Nids with separate sniffer node
Payload Packet size is 91 byte effective (73 when aes cryptography is included)	Compression applied with a static symbol table(to avoid long time analysis)	In ZigBee pro version packet can be fragmented allowing a packet size to be large as the available buffer (compression is still a better solution)
Stack crash due to oversized packets (buffer overflow) or fake command frame	Beta test results were sent to manufacturer	The new stack version (ZigBee PRO) seems to suffer very similar problems

Table 5.6 – Main problems summary

5.7 Practical of experiences on Meshnetics boards

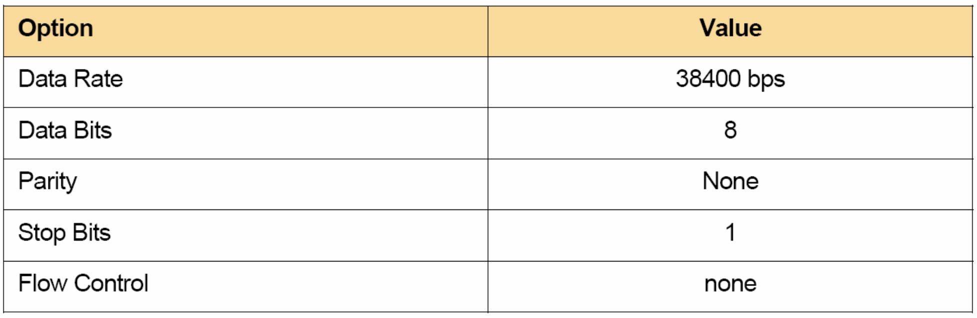
This paragraph want to be a summary of all hardware/software problems found with the provided WSN kit. It does not have any intention to prove the boards' kit to be good or not, but we can assert that ZigBee WSN are young systems and this is proved by the four different specifications release prepared in this last four years. Thus we didn't really expect a mature product ready to use but something useful for the real indoor research.

5.7.1 The hardware analysis

The on board sensors as noted before in this chapter consist in a temperature sensor (LM73) with a declared ±1.0°C (max) accuracy in the -10°C -80°C temperature’s interval. This sensor is to be considered quite good for an environment monitoring system but the on board sensor position is very close to the voltage regulator and its measurements are affected by the regulator heat dissipation. This problem increases greatly when the measurements are near the 0° Celsius. Moreover the difference between two sensors, in the same condition and position are sometimes greater then 4°C, far too much also for an environment’s monitoring system.

To solve this problem was firstly experimented a calibration with several intervals (10 to 20 nominal intervals) and then the temperature sensors were substitute with another, wired, model (Sensirion sht75) including RH measurements capability.

Although the boards are claimed to operate at -20° Celsius and to be as few as possible affected by temperature even less than that point. The test made demonstrates that the node completely stops to send any kind of message at about -3°C and start having radio listen/receive problems just under 0°C . It wasn’t possible to completely evaluate the node internal condition but it seems that the clock and batteries were greatly affected by the temperature condition.



Option	Value
Data Rate	38400 bps
Data Bits	8
Parity	None
Stop Bits	1
Flow Control	none

Table 5.7 - Virtual COM-port recommended settings

The presence of an USB 2.0 port allows the board to be powered directly from a Computer, on the other hand as correctly declared by manufacturer, the instability of USB’s port current greatly affect the sensors’ measurements. Moreover the USB port has a RS-232 to USB bridge controller (model CP2102 from Silicon Labs) that provides a seamless’ connection from the Serial port to the USB port, thus, from an PC Operating System (like windows) the port is visible as a generic, virtual, COM port with a particular OS-given number. Although this system is quite easy to uses and allows to send AT commands over the USB port, the system itself use the speed and characteristics of a serial port (see figure 4.5), this means that instead of a 12Mbps raw data rate of an USB 1.1 (or 480 Mbps for the 2.0). The recommended settings visible in table 4.10 use a 38400 bauds connection (to a maximum of 115000 unusable due to sync problems) that is about 4,5 Kbps (to a max of 12 Kbps). With a great effort we were able to reach a connection speed of 57600 bauds using a rough flow control to test whether the COM connection must be resynchronized.

This bottleneck, coming from the Atmel MCU architecture (and not to a manufacturer fault), dramatically decreases the overall network bandwidth towards the gateway system.

The next μcontroller's generation, which is probably ready nowadays, it's claimed to solve this problem.

The power consumption is another painful aspect of these device. Although these devices are claimed to be very low in power requirement and if we take a look in figure 5.20 we can see it (with a idle period of 0.2 seconds).

The real on field test demonstrates that these nodes are more greedy in power consumption.

In fact with an average power draws of 15 mAh and two AA rechargeable batteries (2000 mAh) we can expect a lifetime of more than five days (well this is far less than the many moths lifetime claimed by ZigBee Alliance) while the test tell us that lifetime is of about 48 hours that means a power consumption average, including idle periods, of more than 40 mAh.

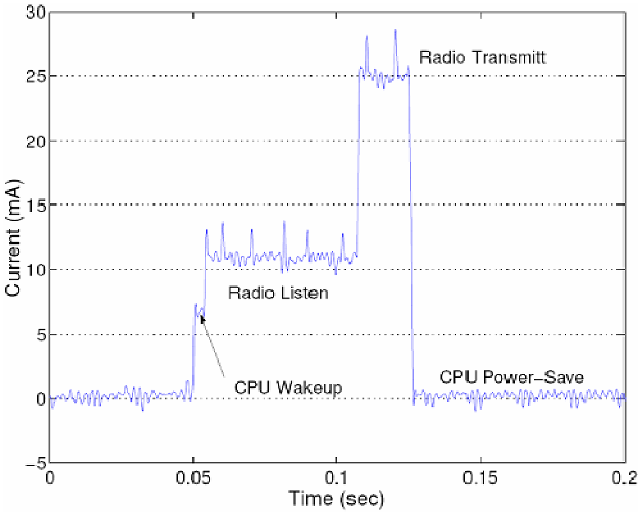


Figure 5.20 – MCU power energy consumption

Of course on our boards there are many sensors and other electric devices (voltage regulators, usb to com bridge, leds etc) and not only the MCU/radio couple. The introduction of beacons followed by deep sleep period has helped to reach these five or even more days of lifetime (see figure 4.19e) but their far from the months advertised by many manufacturers.

On the other hand, if we set the nodes to survive for a full year (beacons every two or more second) we can find out we have only 20 hours (of energy) for measurements, with one sensor [Aky04].

5.7.2 Board changes and additions

The Meshnetics ZigBee boards come with two sensors (see paragraph 5.2.1): a light sensor and a temperature sensor both connected via the I^2C bus. In our researches the light sensor wasn't used yet so nothing can be said about it, although it datasheet described features and the values read seems to be enough correct about the context to say if there was sunlight, artificial light (or cloudy day) or there's no light at all.

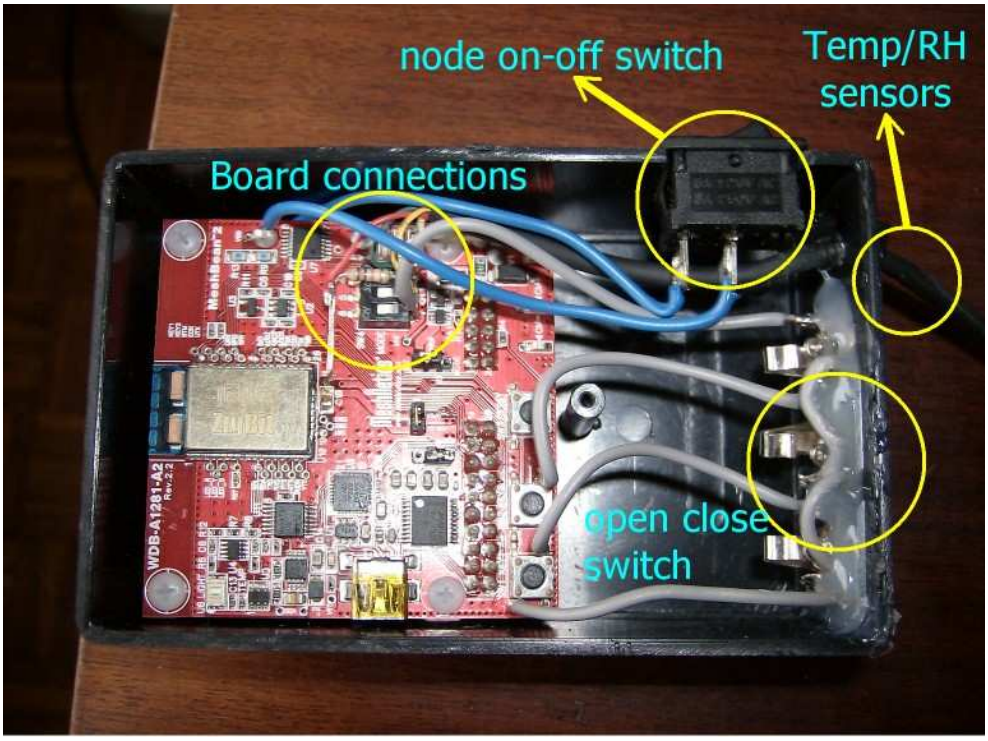


Figure 5.21 –The modified board protected by a plastic box

Instead the temperature sensor does not fit our need due to its precision of ±1°C and its proximity to the voltage regulator (VR) causing its measurements sometimes to be greatly affected by the VR heat.

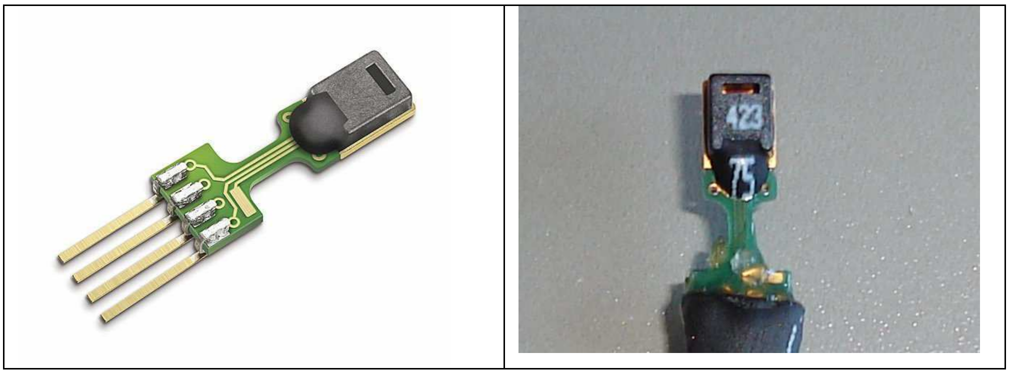


Figure 5.22 –The sensirion SHT75 temperature/Relative Humidity sensor

Moreover the nodes cannot be always inserted in the air flow pipes due to temperature and/or moisture or just because they partially stop the airflow itself.

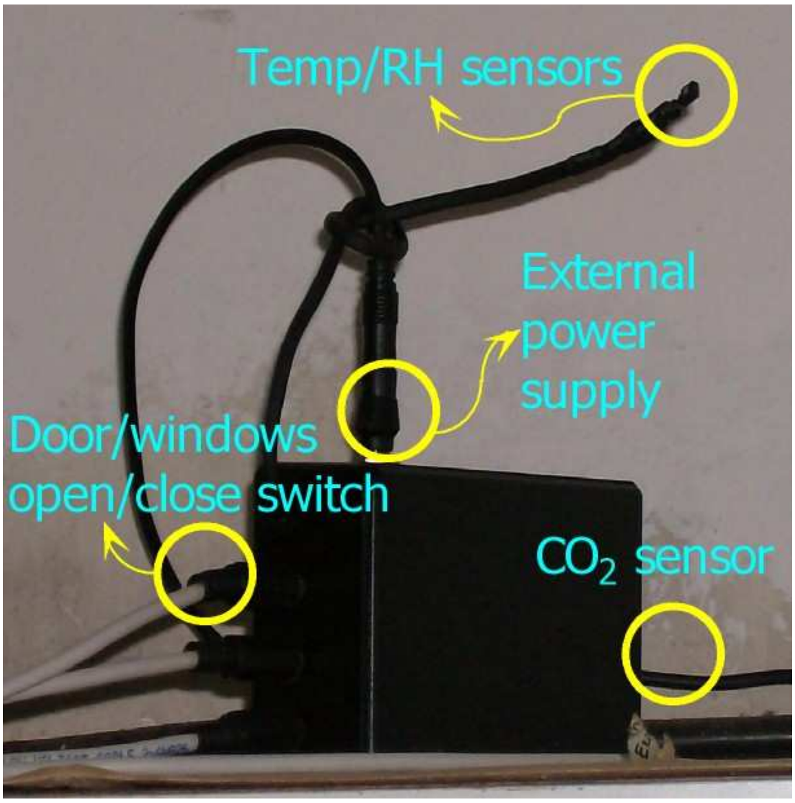


Figure 5.23 –The sensirion SHT75 temperature/Relative Humidity sensor

For these reasons the boards were modified disabling the installed lm73 sensor and installing a better temperature/RH SHT75 sensor produced by Sensirion (precision ±0.3°C, ±3% RH see figure 5.22).

For the first research, were also connected on the boards some open/close switches to control the doors and windows status.

To ease the process of connecting/disconnecting the open/close switch and to protect the board itself, the node was enclosed in a plastic box (for electronic device) with some connector plugs.

The SHT sensor is connected to the board by a little cable allowing the insertion of the sensor inside pipes without the rest of the device.

The figure 5.21 shown the board modifications while in the figure 5.23 can be viewed the box protected node at work.

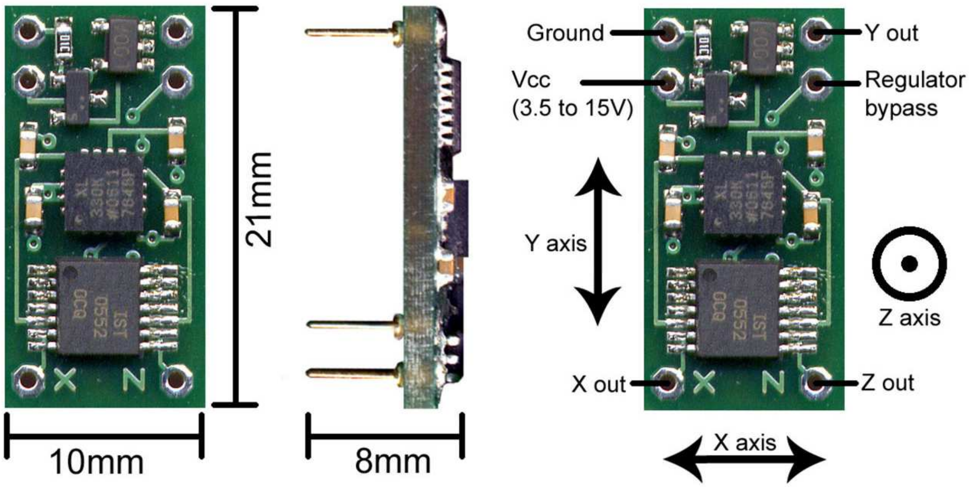


Figure 5.24 – the DE-ACCM3D accelerometer

For the second research, instead, it was needed a node with a 3-axis accelerometer. These accelerometers (many accelerometers were tested for this purpose, see the de-accm3d in figure 5.24) can record samples at thirty hertz per axis (most of them can reach 160 Hz or even higher rates).

5.7.3 Extracting Keys from Second Generation Zigbee Chips

This special section may be considered as part of physical attacks as described in Appendix A.1.2.1.

The paragraph will describe the state-of-the-art of physical attacks against ZigBee networks and their implementation of security. All the literature involved is written and published during the years 2008 and 2009, and as far as I know they are still up to date .

This experience can be easily completed with few tools and the author have also partially achieved the task. In our situation in fact there's no a on-board hole has in figure 5.25 where we can fix the needle and we stop the test just to avoid any scratch that can irreparably damage the board itself-.

The First generation of ZigBee chips were simply digital radios with a SPI interfaces and hardware-accelerated cryptography. They relied completely upon an external microcontroller to perform even the basic functions such as run a ZigBee stack. [Goo09]

This first generation chips send the security keys as clear text between their components which can be easily sniffed by an SPI-device allowing an attacker to participate in a network.

The second generation of ZigBee chips, the ones used in this thesis, hold a complete ZigBee implementation internally, thanks to a reprogrammable microcontroller.

They may also lack the vulnerability to bus probing, as keys need not travel over an exposed SPI bus. The microcontroller cores were added for convenience, not security.

The third generation of chips, which is almost ready will include more powerful microprocessors and hopefully more security, but these chips are out of our study as they are not yet commercially available yet.

Although some datasheet and various literature claim that some microcontroller, for example the EM250, employs a configurable memory protection scheme usually found on larger microcontrollers this refers to protection from accidental self-corruption of memory not to a debugging fuse or boot loader password.

This protection allow the ZigBee stack to defend certain regions of RAM and radio registers from accidental corruption by the application itself [Goo09].

In any case, the debugging port of these chips does not contain a security fuse. There is no supported method of denying access to an attacker who controls those pins. Most manufacturers such as Atmel and Ember are aware of the oversight, and their third generation (like EM300 series) does not share this vulnerability, instead, there are presently no plans to fix the second generation chips.

The author of [Goo09] uses a GoodFET1 USB bus adapter implementing a JTAG protocol, developed by the author himself to prove the vulnerability described. Its adapter's firmware includes support for the debugging protocol as documented in programming interface specification (in this case of Chipcon), allowing the radios to be debugged using a python script.

This vulnerability can be tested for on any Chipcon device and many other microcontroller of different manufacturer and is strictly dependent from a RAM non deletion by the *CHIP ERASE* procedure.

The Key identification within non-key data has been demonstrated in various articles such as [HSH08] where the authors manage to reliably identify disk encryption keys from DRAM, and they conclude with the statement that it might become necessary to treat DRAM as untrusted, and to avoid storing sensitive information there, but this will not become feasible until architectures are changed to give software a safe place to keep its keys.

While personal computers and several microcontrollers like the EM250 might lack such a place, it is possible to instruct several compiler to store a constant in Code (Flash) memory, rather than in Data (RAM).

This is also described in [HSH08], but as a workaround for RAM limitations rather than as a security measure.

The *code* keyword must be applied to all const variable as well as any pointer to such a constant. This is due to most microcontrollers such as the 8051, as a Harvard machine, that does not have a unified address space.

Must be noted that there is a performance penalty to fetches from code memory, as they cannot occur at the same time as an instruction fetch.

The author of [Goo09] demonstrate how a Chipcon radios at the time of publication are vulnerable to key theft because of unprotected Data memory.

In the same paper he demonstrates how Ember radios offer even less security. Extracting a key is as simple as connecting a debugger, erasing the chip, then freely reading the contents of DRAM.

Further, the same author in [GoT09] illustrates and proves how to brake the AES 128 security in other μcontroller such as MSP430 and the AVR family.

In this case it is a attacked the hardware-accelerated AES128 implementation, by taking advantage of the fact that keys must be loaded over the SPI bus.

In the fig 5.25 it’s shown how to tap one of three SPI pins of the CC2420 radio chip (on a Telos B node) using a hypodermic syringe.

The SPI bus consists of four lines: SCL, MOSI, MISO, and !SS. SCL is the serial clock and is output helps to synchronize communications with the slave devices.

MOSI and MISO are data lines, respectively Master Out Slave In and Master In Slave Out.

Finally !SS or Slave Select is an inverted line to indicate the slave chip’s selection. In the figure 5.25 [Goo09], it is tapped only SCL line, and only one of the data lines will be used just to simplify the test. Since the ground is shared by USB it is not necessary to tap it.

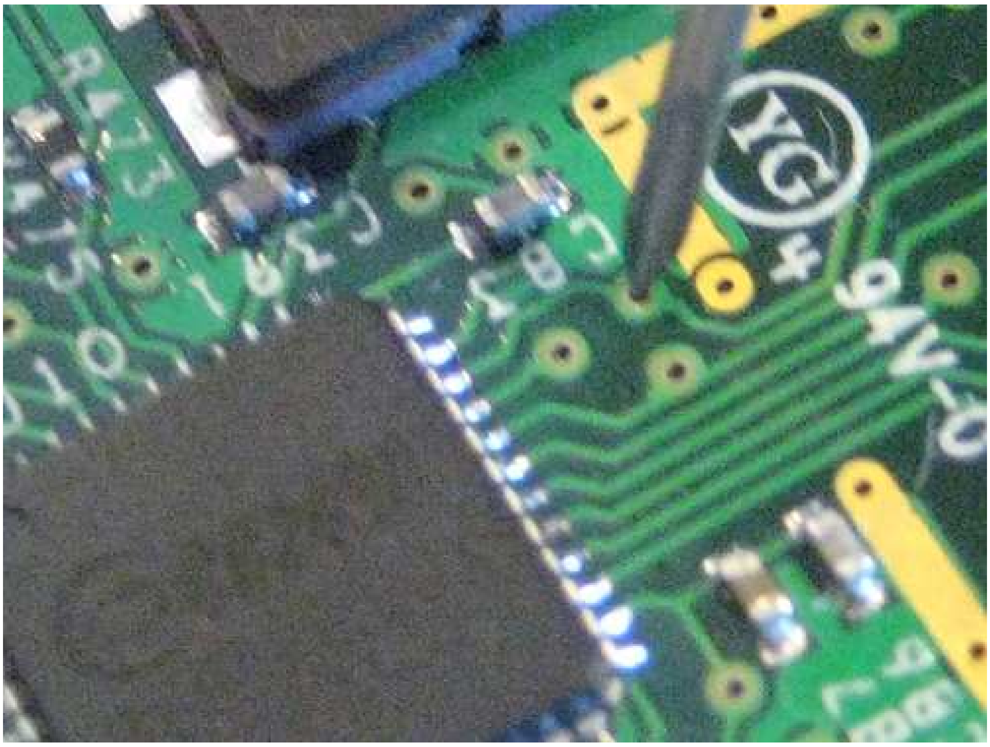


Figure 5.25 - An active attacks

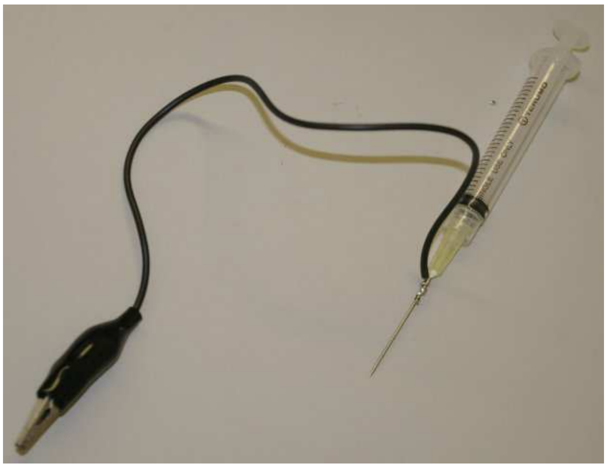


Figure 5.26 – the syringe tool

As shown in figure 5.27 (portable scope), the tapped pin is the SCL, the data clock.

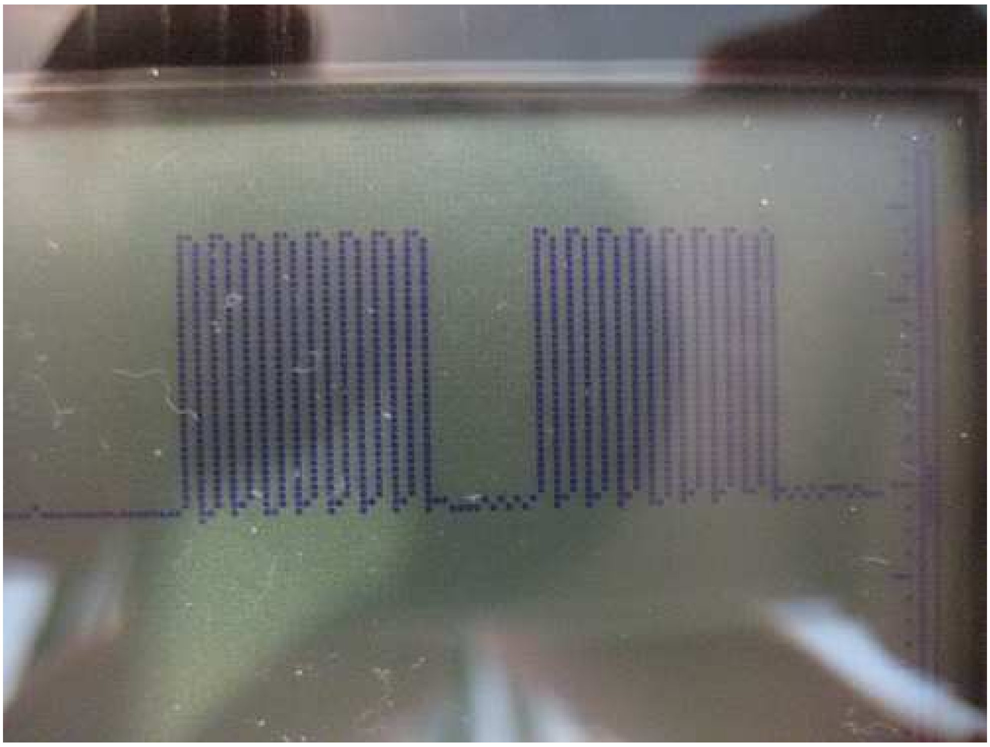


Figure 5.27 - SCL signal (on portable scope)

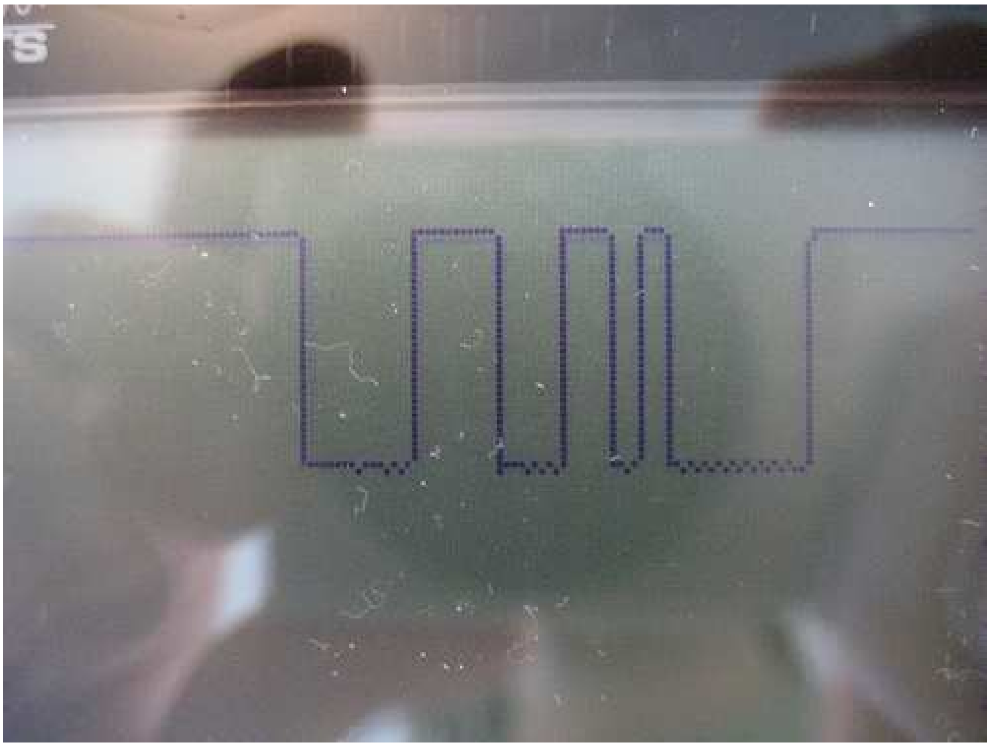


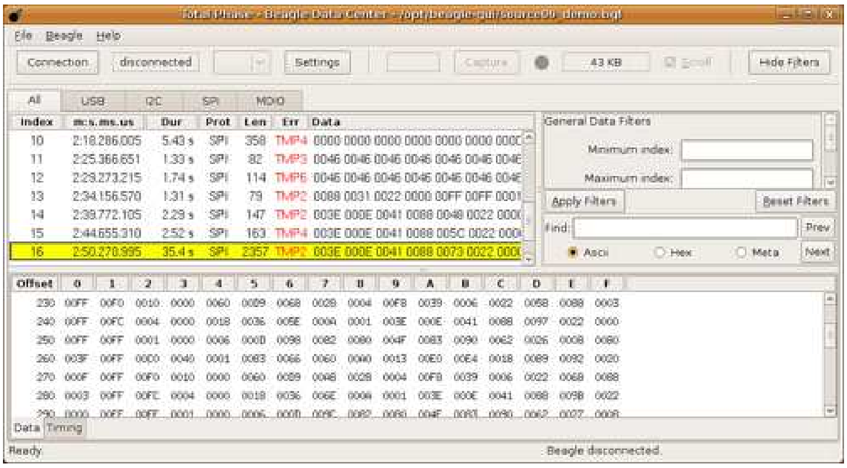
Figure 5.28 - data signal (on portable scope)

The clock stands out because it idles low, and because all pulses in a batch are of regular width. Unlike a system clock, the clock only cycles when data is being transported.

The remaining two pins, in the group of three, are data. As shown on the scope image 5.28, SPI data lines idle high, and bits are measures on edges of the clock.

When the clock and data lines have been found, it is necessary to sniff the traffic using a bus adapter. In this example Total Phase Beagle I2C/SPI Protocol Analyzer it is used as shown in figure 5.29 (now it is available the SPI-sniffing firmware for the Hackaday Bus Pirate claimed to be much more powerful). A screenshot of the Total Phase client follows.

All that remains to identify the key in use, or anything else sent over the bus, is to read the log or to analyze with a script in search of the AES key.



Index	m:s.ms.us	Dur	Prot	Len	Err	Data
10	2:18.286.005	5.43 s	SPI	358	TMP4	0000 0000 0000 0000 0000 0000 000C
11	2:25.366.651	1.33 s	SPI	82	TMP3	0046 0046 0046 0046 0046 0046 004E
12	2:29.273.215	1.74 s	SPI	114	TMP6	0046 0046 0046 0046 0046 0046 004E
13	2:34.156.570	1.31 s	SPI	79	TMP2	0088 0031 0022 0000 00FF 00FF 0001
14	2:39.772.105	2.29 s	SPI	147	TMP2	003E 000E 0041 0088 0048 0022 000(
15	2:44.655.310	2.52 s	SPI	163	TMP4	003E 000E 0041 0088 005C 0022 000(
16	2:50.270.995	35.4 s	SPI	2357	TMP2	003E 000E 0041 0088 0073 0022 000(

● Ascii ○ Hex ○ Meta

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
230	00FF	00F0	0010	0000	0060	0009	0068	0028	0004	00F8	0039	0006	0022	0058	0088	0003
240	00FF	00FC	0004	0000	0018	0036	005E	000A	0001	003E	000E	0041	0088	0097	0022	0000
250	00FF	00FF	0001	0000	0006	000D	0098	0082	0080	004F	0083	0090	0062	0026	0008	0080
260	003F	00FF	00C0	0040	0001	0083	0066	0060	0040	0013	00E0	00E4	0018	0089	0092	0020
270	000F	00FF	00F0	0010	0000	0060	0089	0048	0028	0004	00F8	0039	0006	0022	0068	0088
280	0003	00FF	00FC	0004	0000	0018	0036	006E	0008	0001	003E	000E	0041	0088	009B	0022
290	0000	00FF	00FF	0001	0000	0006	000D	009C	0082	0080	004F	0083	0090	0062	0027	0008

Ready

Beagle disconnected.

Figure 5.29 –Data sniffer

6
Results

6.1 WSN performance benchmarks

The application development had a long test period in which many functionalities were observed. The first on field research was intensively used also as the WSN test-bed due to the long period required to gather all information (more than one year). Moreover in the same period were used as data backup the buttons sensor (with only purpose of measuring temperature and relative humidity values) from Dallas Semiconductor.

These button-shaped sensors, the only practical resource before the WSN introduction, can stay into place, gathering data for two weeks (one measurement each five minutes) and then require a user to download the data, for each button, to export the saved data to a useful format (text delimited), to reprogram the buttons and, finally reposition them accordingly to their position's number, to start again the gathering (This require about two work-hours for a single person to complete the task). Additionally if a sensor is not working because of any reason (i.e. bad reprogram) the full two weeks' data will be lost.

The features observed in our WSN system were:

- Network performance regarding topology used
- Sensor efficiency and precision
- Network reliability and fault tolerance

These features help to take several decision, like network topology, sensor in use what kind of fault tolerance may be useful.

6.1.1 Application performance

First of all must be noted that our WSN system cover a little area (a house) and is formed by less than twenty nodes. This is due to the main task we want to achieve: an on-field indoor research system as automatic and non-invasive as possible.

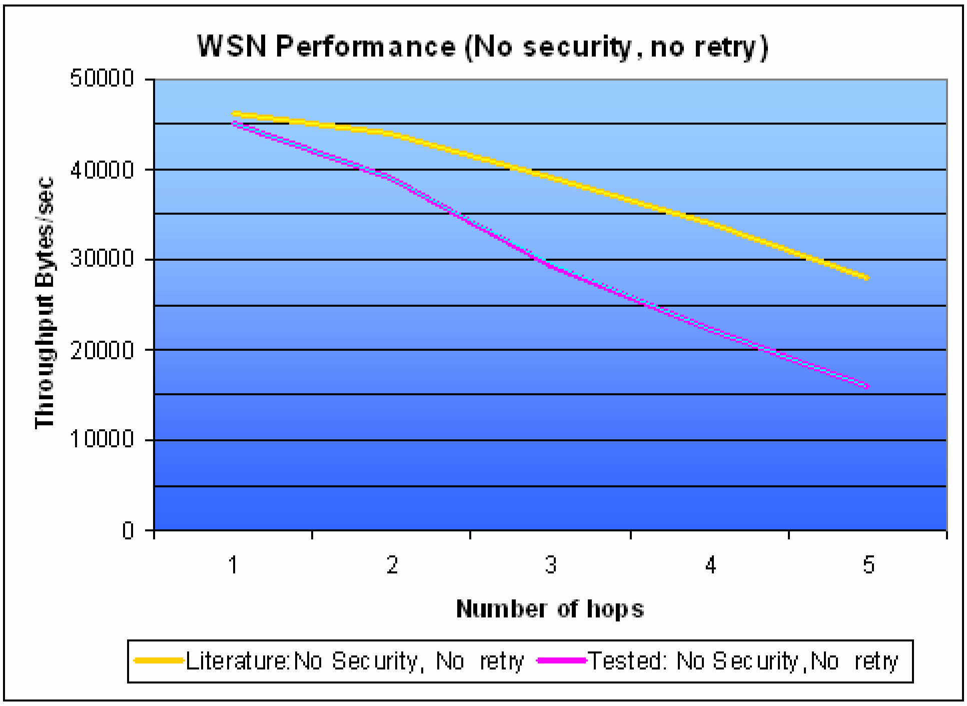


Figure 6.1–Application performance (No security, no retry)

In this comparison the literature is represented by the ZigBee alliance itself (www.zigbee.org). The measurements for our tests were made sending one thousand packets (the same packet) from the farthest node to the PAN coordinator. This process was repeated one hundred times in different daily moments.

The overall network performance is important since it says the real bandwidth available to a node and its data flow. The literature has usually tested these WSN in open space or in laboratory while our situation is in a common and real inhabited apartment.

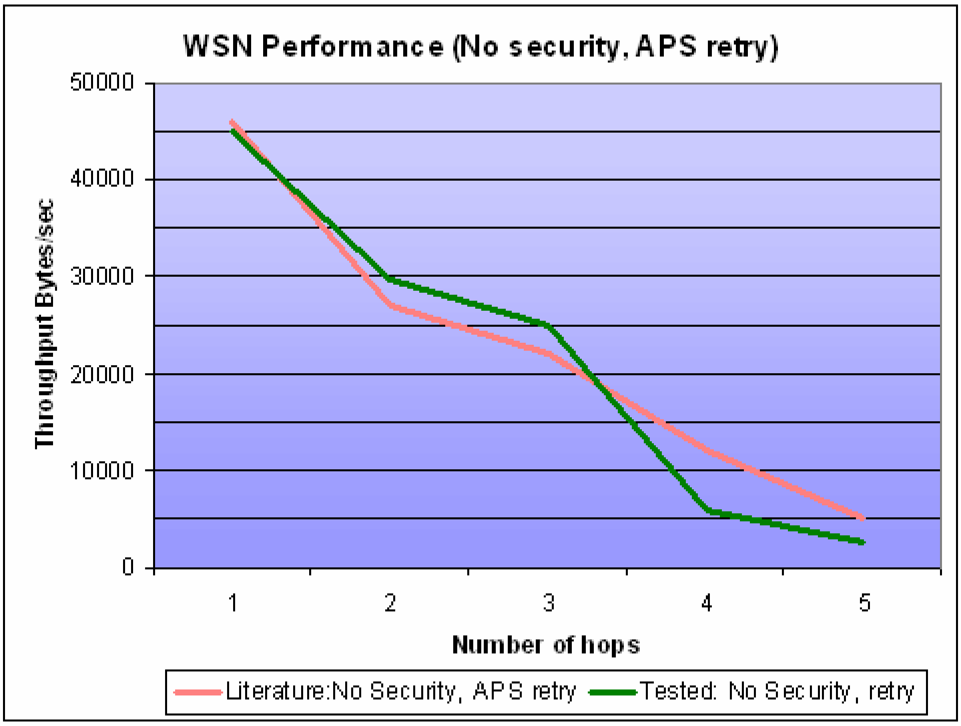


Figure 6.2 –Application performance (No security, APS retry)

As we expected the performance is worse than the ones proposed by many specialized articles (i.e. [Mis07] and [BPC07]) and the ZigBee Alliance itself (zigbee.org).

Of course the main reason to this decrease in performance results due to the possible signal' interferences in our environment, where many wi-fi networks coexist and, moreover, a lot of electronic devices are powered up (and turned off) continuously thus we can consider our research field as a WSN hostile environment.

In favor of our results we can say that the performance degradation is much more visible after the first three hops, and this is important since our network covers all the apartment's area within three hops, and usually in just one a direct hop (to reach the five hops we had to put the nodes outside the apartment itself).

The figures 6.1, 6.2 and 6.3 shown the performance results compared to the ones coming from the literature under different network configurations. Must be noted that the retry option (the message re-send on error) greatly reduce the performance (but of course it ensure the reception of the messages).

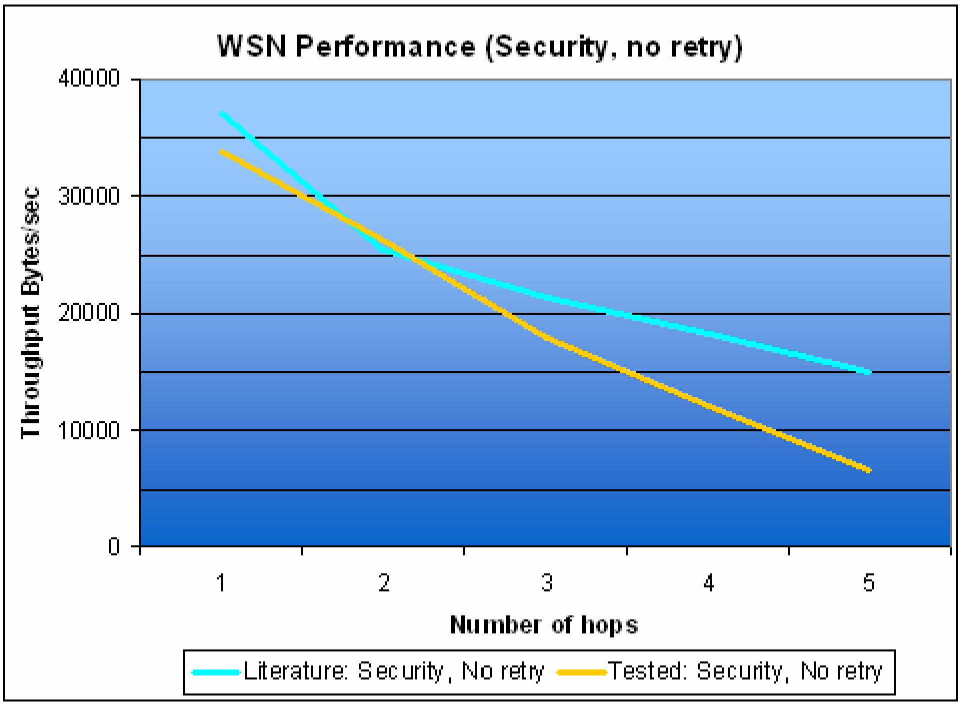


Figure 6.3 –Application performance (Security, no retry)

Instead figures 6.4 and 6.5 illustrate the differences between the to two main topologies considered: mesh and tree regardless the throughput and the battery lifetime.

Although the mesh offers more fault tolerance characteristics the results tell us that the difference is not appreciable in our environment (and with one which have less than twenty nodes) unless we have more than four hops distance between the source and destination nodes.

The possible causes could be the relative few nodes disposed and the small covered area in which a node, in a tree topology, that can’t see the parent any more can just try to rejoin the network asking to another node in its radio range.

Under this condition a node, receiving a join request, can automatically promotes itself to the router role and, if necessary, allow join of the isolated node.

On the other hand is very interesting the lifetime that we can obtain by exploiting the tree topology.

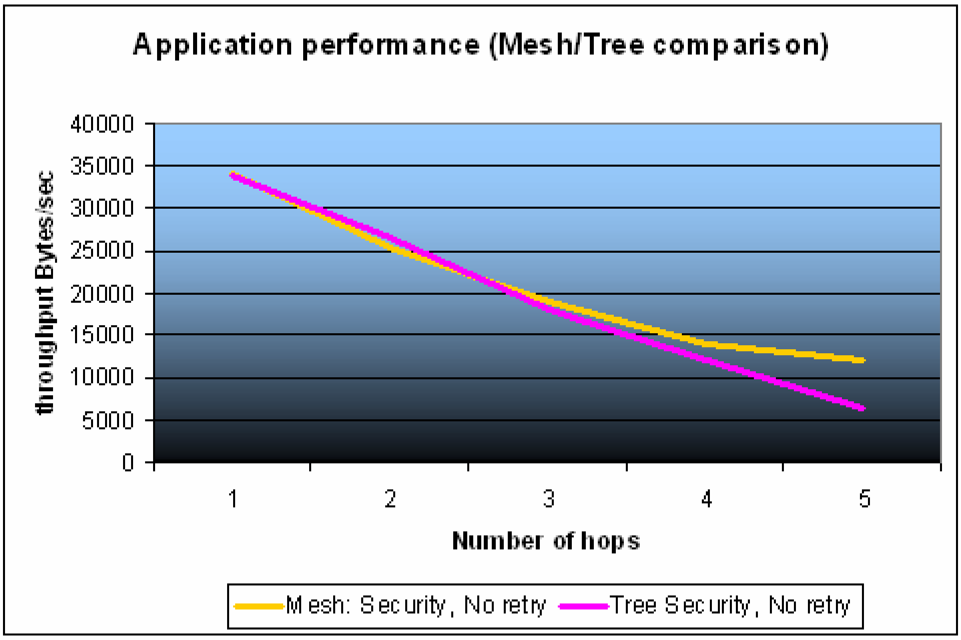


Figure 6.4 –Application performance (Mesh vs Tree)

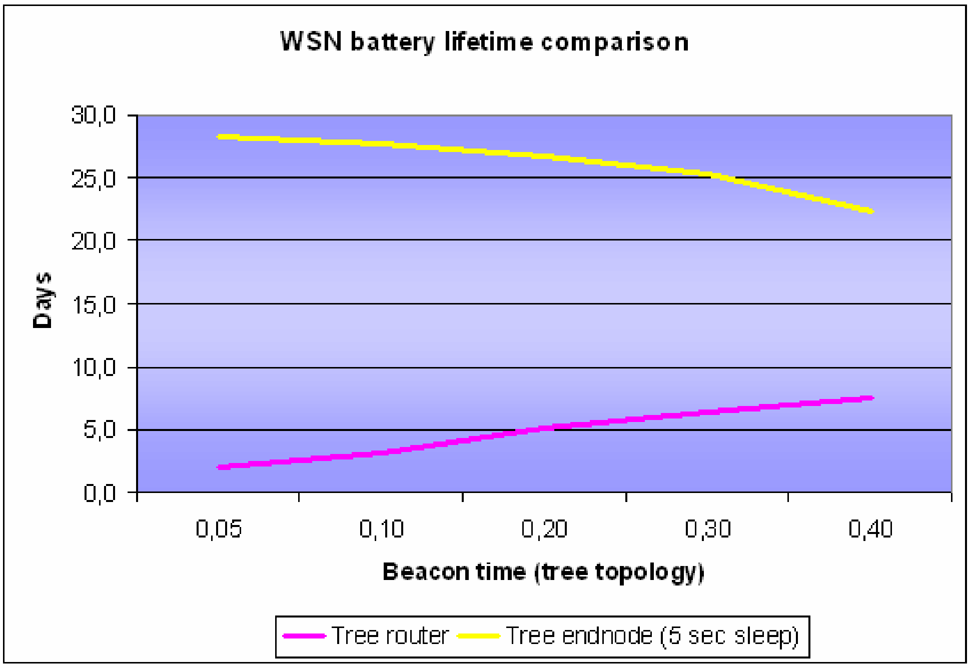


Figure 6.5 –Nodes lifetime in tree topology, they are to be compared of approximately 46 hours of lifetime of mesh nodes

In the graph depicted in figure 6.5 we can observe how a end-node in a tree topology can reach a lifetime of about one month, while can triple the routers lifetime via the beacons period.

Appling the algorithm shown in figure 6.6,6.7 and 6.8, we can obtain that all nodes have an average lifetime of about two weeks due to a ‘role rotation’.

In fact a router R when sees its battery power decreasing under a certain value, it sends a network message asking for a new router candidate. When the node sends the message it specifies who is its parent and its battery power value. All the end-node upon receive the message check their power energy and if (and only if) their power is more (of the decided quantity) they also check if they can see the P node (if they are in the P range).

If both the conditions are satisfied then the end node will answer the help request, sending their battery power and also their RSSI values for the node P (it’s a way to measure the strength of signal they receive from P). The router receiving the answers use a raw bully algorithm based on power energies and then the RSSI values (if the first values are equal) to decide the winner. Finally the router device acknowledges to the winner node (all the other node will receive the same message indicating the new router) and start the tree leave procedure.

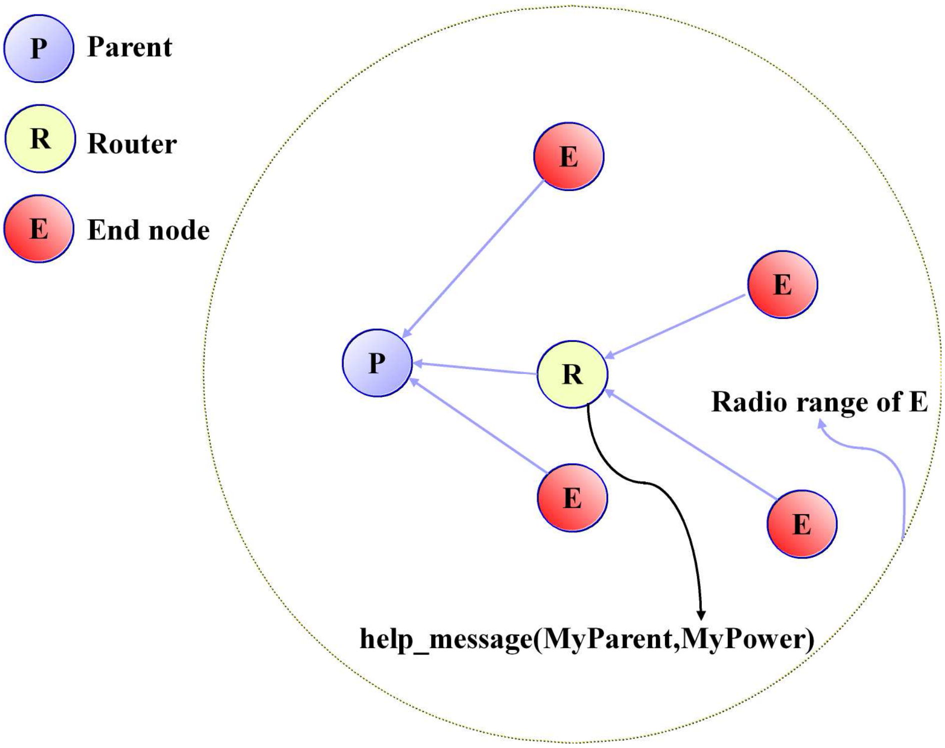


Figure 6.6 –Phase 1: Router ask to change

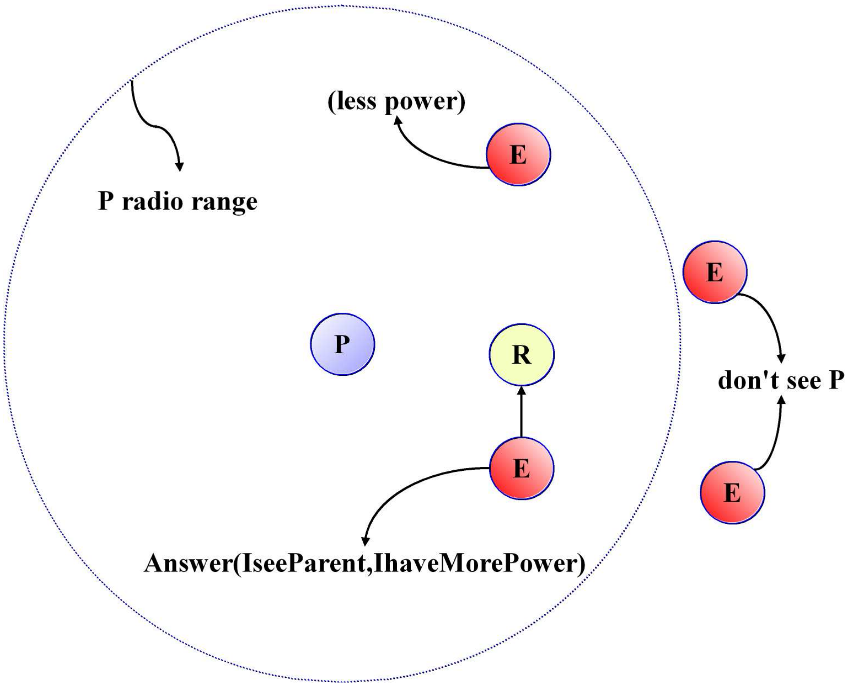


Figure 6.7 –Phase 2: The new candidate answer

In our WSN the beacons were set to be sent every 0,25 seconds allowing about one week of battery lifetime for the router and more than three weeks for the end nodes.

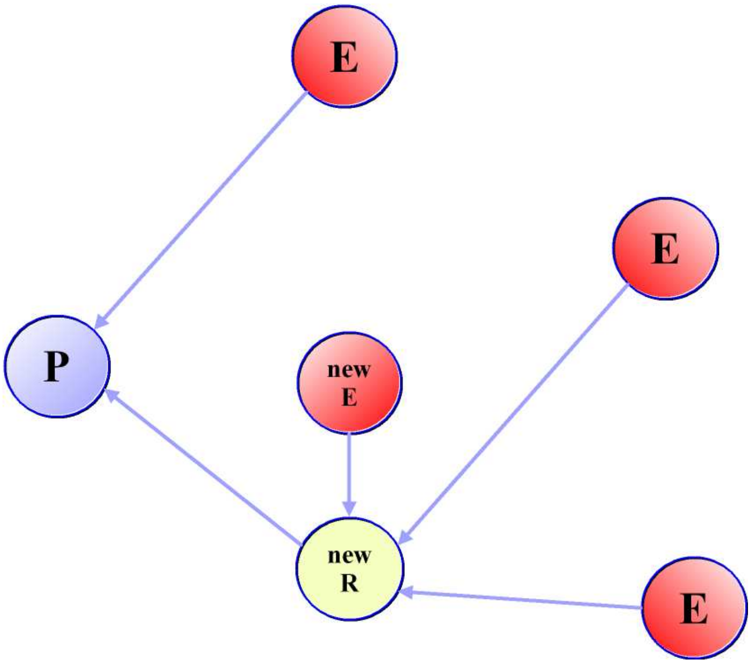


Figure 6.8 –Phase 3: The new tree structure

The new router after the leave procedure will immediately start the join procedure as a router, while the other end-device will perform a rejoin.
Of course, it must be possible to switch a router device back to be an end-node role, which means the router is not part of an heartbeat system or its gathering requirements are not continuous (for instance the node has an accelerometer sampling at 30 values per minute and per axis).

6.2 On-field test application I

The first research started in June 2007 and its aim was to characterize the qualitative and quantitative performance obtained from mechanical ventilation systems (HVAC system) for residential use, in comparison to the traditional systems of natural ventilation [MRB07].
The research was performed by CIAS (Centro Ricerche Ambienti Alta Sterilità - High Sterility's Environments Research Center) Laboratory from the University of Ferrara, together with Aldes France research and development centers of Lion and Modena (Aldes is an HVAC manufacturer) and the DREAM laboratory of the University of Palermo (for the sensors).
Although the HVAC's systems in Europe are relatively common in residential buildings, in literature there are few articles which compare energy saving to natural ventilation system. Moreover usually do not take in consideration experimental data about the obtained energy saving compared to the natural ventilation system. The literature about aspects such as Indoor Air Quality (IAQ) use even less experimental data.
These information lack is partially due to the difficulties of the realization of a non-invasive monitoring system which continuously gather data for long period of time.
For this reasons our study also wanted to take into account several factors such as energy aspects, IAQ comfort (comfort aspects concerning thermo hygrometric, olfactory, CO_2, pollution and microbiological parameters)

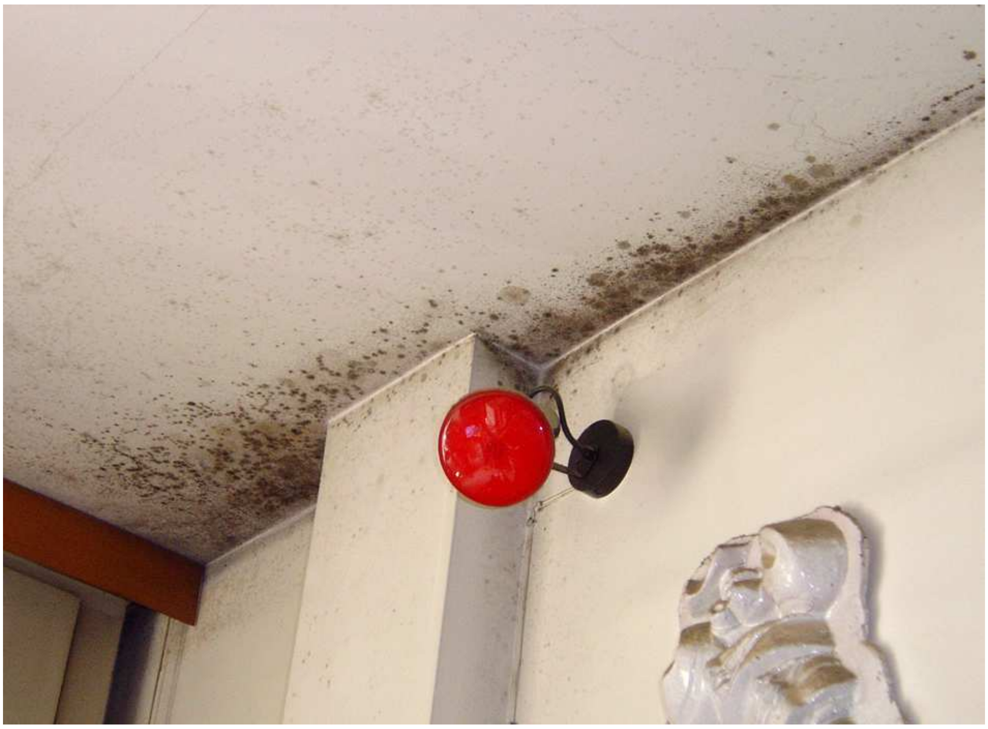


Figure 6.9 – Ceiling's mould in the apartment

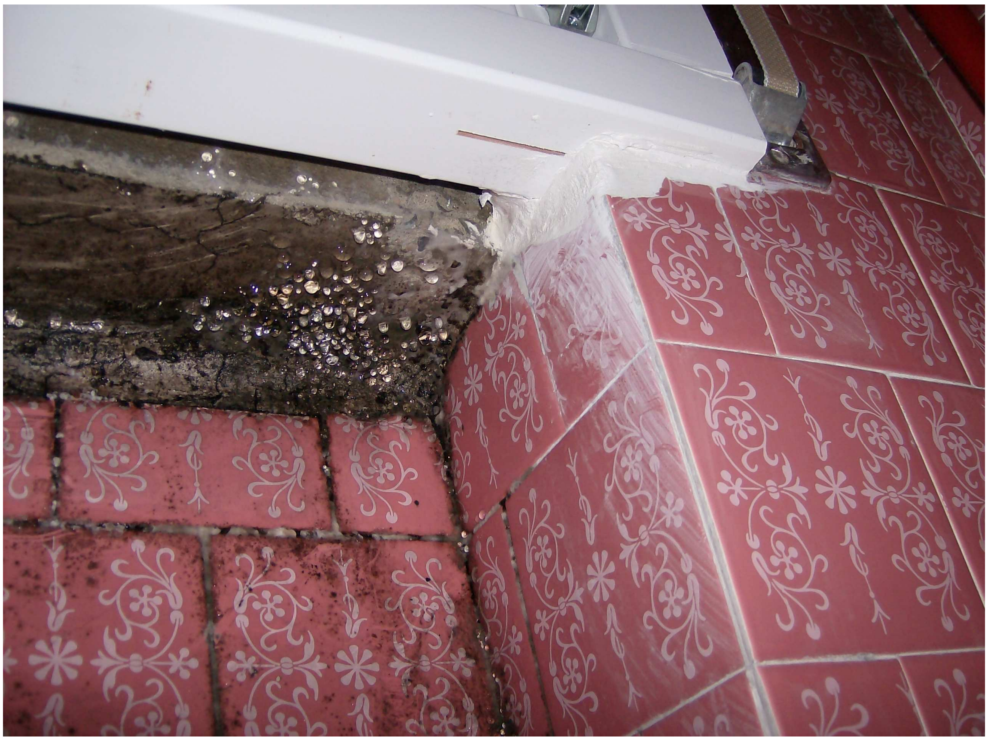


Figure 6.10 - wall moisture's droplets

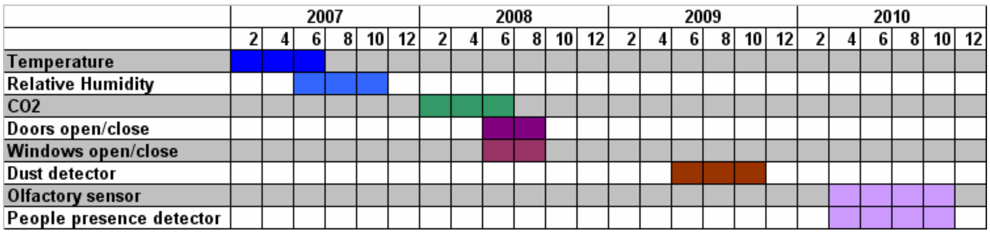
The research's objective requires the use of a real inhabited place and, for this purpose, was chosen a 110 m^2 apartment in Ferrara with a living family consisting of three persons where was installed a mechanical ventilation system with dust filters.

FERRARA	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average maximun temp	4°C	8°C	13°C	18°C	22°C	27°C	29°C	29°C	25°C	19°C	11°C	6°C
Average minimun temp	-2°C	1°C	4°C	7°C	12°C	16°C	18°C	18°C	14°C	10°C	4°C	-1°C
Average rainfall	43 mm	46 mm	61 mm	66 mm	66 mm	53 mm	43 mm	58 mm	61 mm	71 mm	81 mm	61 mm

Table 6.1 – Ferrara's climatic data

The apartment is situated at the fourth floor of a building, consisting in fifteen apartments and five floors, close to the city centre (near the pedestrian area).

The city of Ferrara is located in a flat area, with a lot of moist due to the proximity to the river Po.



	2007						2008						2009						2010					
	2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10	12
Temperature	■	■	■																					
Relative Humidity			■	■	■																			
CO2							■	■	■															
Doors open/close									■	■														
Windows open/close									■	■														
Dust detector															■	■	■							
Olfactory sensor																				■	■	■	■	
People presence detector																				■	■	■	■	

Figure 6.11 – node sensor's implementation (past-present and future)

The urban area is particularly polluted due to the chemical industries situated in the northern part and to the city cars traffic (the legal limit for PM10 dust is exceeded tens times a year).

The chosen apartment has many problems generating great discomfort coming from the moisture visible in figures (6.9 and 6.10). The HVAC system is claimed to remove the moisture thus to eliminate the mould generation.

The monitoring system consists in the wireless sensor network developed in this thesis and in the hardware and software that make the data available in real time to the researchers. Also this part of the system was developed by the author.

It must be noted that some measurements such as microbiological findings, due to their nature, were taken manually by two biologist.

The interdisciplinary character of this study involves different types of researchers such as medical, biologists , engineers (apart from IT staff).
The monitoring system is designed to potentially perform more tasks than the ones actually carried out in our on field application test as we can see in figure 6.11.
This monitoring system has produced a significant quantity of data (a hundreds of gigabyte) which allow a deep analysis of the different aspects as planned.

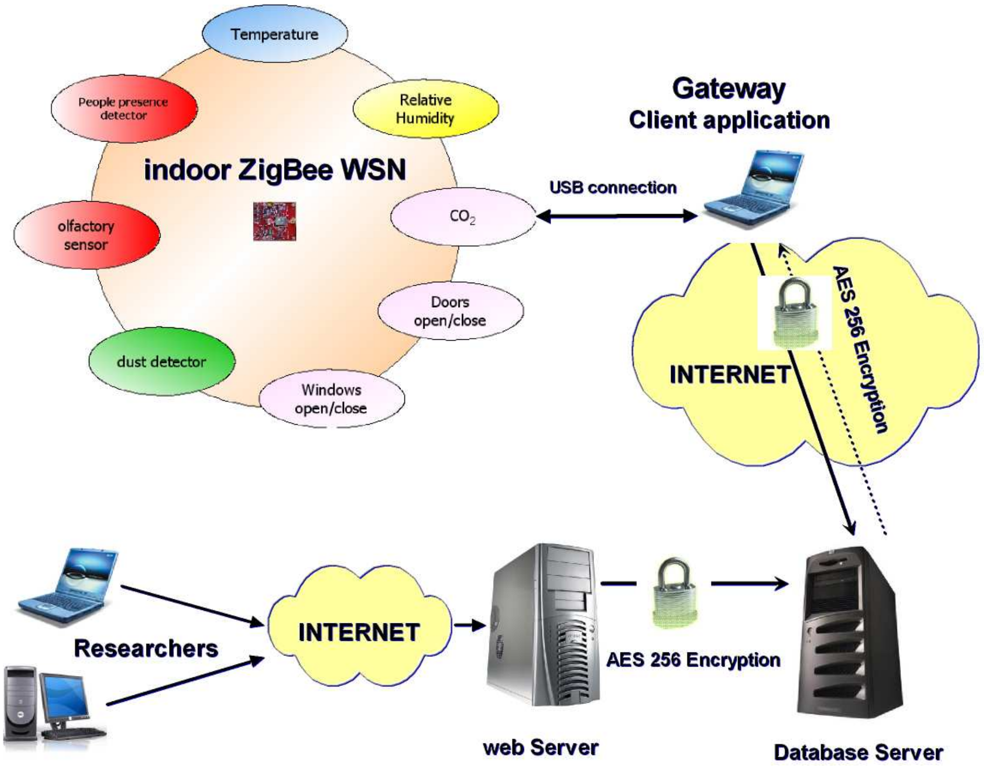


Figure 6.12 – First research’s system architecture

6.2.1 The monitoring system

The monitoring system is formed by the WSN gathering data automatically and a gateway application which receives data from the PAN coordinator via an USB (a virtual COM port).
The gateway application after a data validation splits the data according to the Database structure and then inserts the new rows in the Database server.

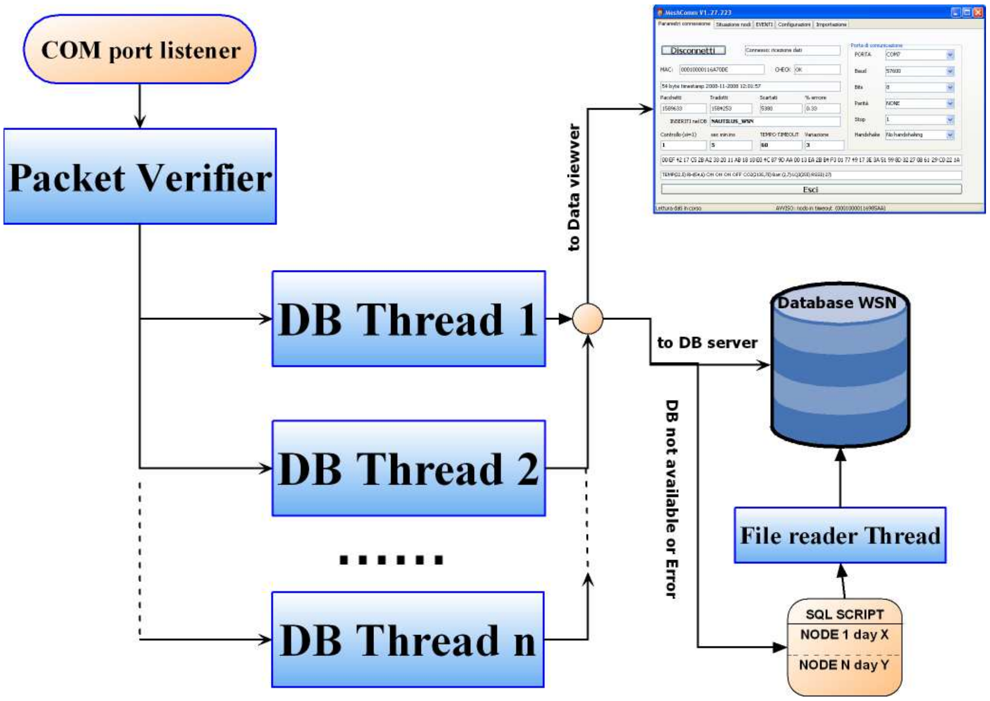
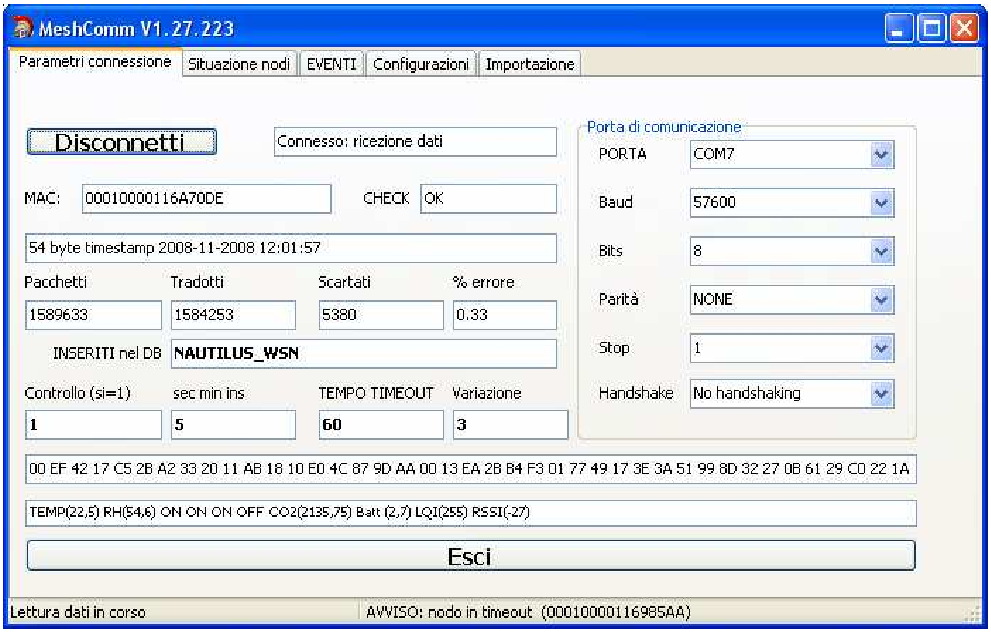


Figure 6.13 – Gateway application

The application was organized via separate threads as depicted in figure 6.13 where each node can be treated by a single database thread which performs the required checks and, when necessary, executes the data conversion to fit the database format. The main application window is shown in figure 6.14.

The last application version can be configured to use one thread for many nodes or, vice versa, to specialize one thread for one node (it was done for the node having high data flow). In this way instead of using N threads, we can use just one thread for all the nodes, if they gather data at low rate (e.g. temp, RH and CO_2), and one more thread for each node requiring special attention (e.g. gathering accelerometer's data).

If, for any reason, the client cannot reach the DB, it stores the information into an SQL script file ready to be executed. In this way, the client can be fully operative even without an internet connection and an available local DB server but, without a working database, the data are not available in real time.



Connesso: ricezione dati

MAC: 00010000116A70DE

CHECK OK

54 byte timestamp 2008-11-2008 12:01:57

Pacchetti	Tradotti	Scartati	% errore
1589633	1584253	5380	0.33

INSERITI nel DB **NAUTILUS_WSN**

Controllo (si=1)	sec min ins	TEMPO TIMEOUT	Variazione
1	**5**	**60**	**3**

Porta di comunicazione

PORTA	COM7
Baud	57600
Bits	8
Parità	NONE
Stop	1
Handshake	No handshaking

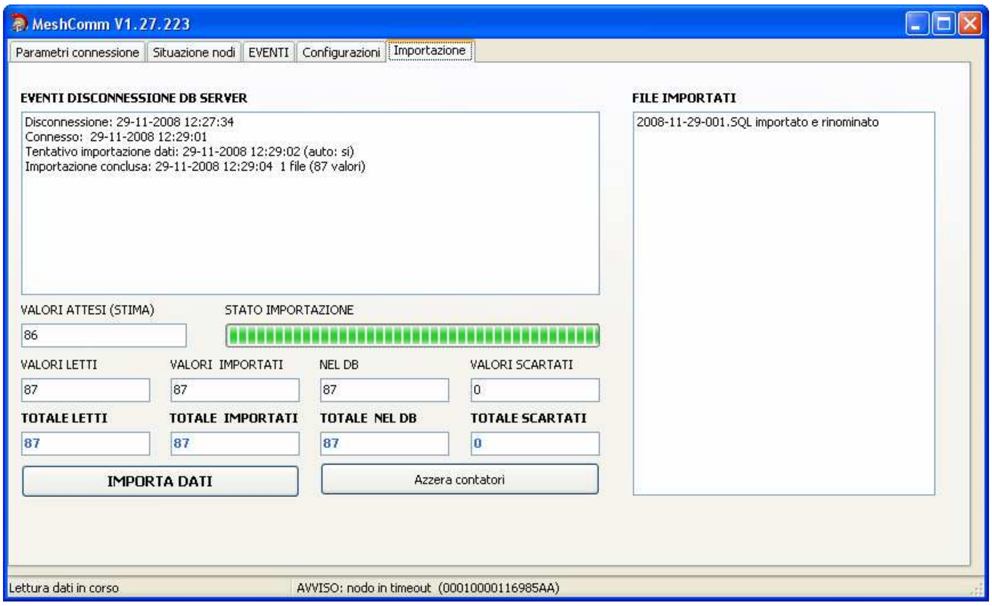
```
00 EF 42 17 C5 2B A2 33 20 11 AB 18 10 E0 4C 87 9D AA 00 13 EA 2B B4 F3 01 77 49 17 3E 3A 51 99 8D 32 27 0B 61 29 C0 22 1A
```

```
TEMP(22,5) RH(54,6) ON ON ON OFF CO2(2135,75) Batt (2,7) LQI(255) RSSI(-27)
```

Lettura dati in corso

AVVISO: nodo in timeout (00010000116985AA)

Figure 6.14 –Application main window



EVENTI DISCONNESSIONE DB SERVER

```
Disconnessione: 29-11-2008 12:27:34
Connesso:  29-11-2008 12:29:01
Tentativo importazione dati: 29-11-2008 12:29:02 (auto: si)
Importazione conclusa: 29-11-2008 12:29:04  1 file (87 valori)
```

FILE IMPORTATI

```
2008-11-29-001.SQL importato e rinominato
```

VALORI ATTESI (STIMA) 86

VALORI LETTI	VALORI IMPORTATI	NEL DB	VALORI SCARTATI
87	87	87	0
TOTALE LETTI	**TOTALE IMPORTATI**	**TOTALE NEL DB**	**TOTALE SCARTATI**
87	**87**	**87**	**0**

Lettura dati in corso

AVVISO: nodo in timeout (00010000116985AA)

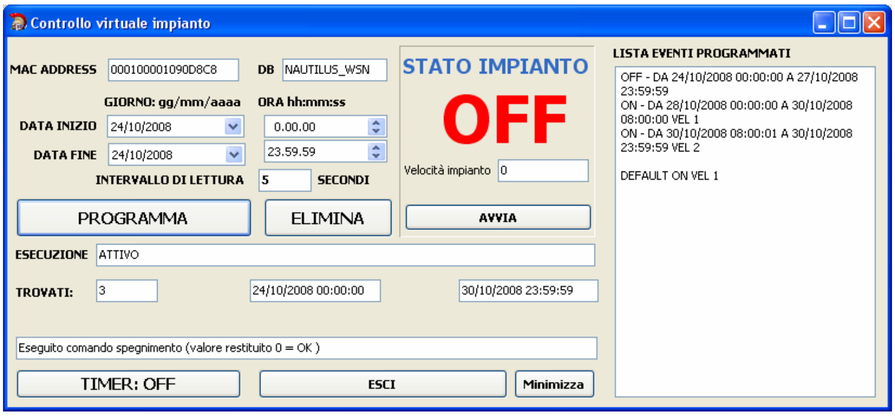
Figure 6.15 –File reader window (the application thread)

A file reader thread is activated when the DB is not available and performs a periodic DB connection check. When this thread find a useful connection to the DB it starts reading the SQL data’s script inserting the rows into the newly on-line database as can be seen in figure 6.15.

The only application prerequisite is that the Database server must be reachable at the start of the application itself because it needs to check the password and the access rights and needs to load the sensors information and calibration values. If this condition is not met, the file reader cannot perform any action and must be invoked manually as an external application providing the right password.
In this last situation, without a db connection from the beginning, it must be prepared a local configuration file for the nodes and sensors data.
The configuration file has the following structure (a tipical windows config file):

```
[node_mac_address]
id1=sensorid      ; the integer sensor id in database

type=typeid
; type id (temp/rh...) as in database

calib=value ; single real value or NONE keyword
;or ApplyOnInsert (if there are values for each range)

id2=...
```

There is no need to insert any position's information since they must be already in the database at the rows' insertion time.



Controllo virtuale impianto

MAC ADDRESS 000100001090D8C8 DB NAUTILUS_WSN

GIORNO: gg/mm/aaaa ORA hh:mm:ss

DATA INIZIO 24/10/2008 0.00.00

DATA FINE 24/10/2008 23.59.59

INTERVALLO DI LETTURA 5 SECONDI

STATO IMPIANTO

OFF

Velocità impianto 0

ESECUZIONE ATTIVO

TROVATI: 3 24/10/2008 00:00:00 30/10/2008 23:59:59

Eseguito comando spegnimento (valore restituito 0 = OK)

LISTA EVENTI PROGRAMMATI

OFF - DA 24/10/2008 00:00:00 A 27/10/2008 23:59:59
ON - DA 28/10/2008 00:00:00 A 30/10/2008 08:00:00 VEL 1
ON - DA 30/10/2008 08:00:01 A 30/10/2008 23:59:59 VEL 2

DEFAULT ON VEL 1

Figure 6.16 –HVAC virtual control

A special thread was developed to control, via WSN node's command, the HVAC plant. This thread can be pre-programmed to switch the plant on or off, and to change the plant speed. A timer will provide the support to send the commands at the right time. An user can also directly change the plant properties overriding the programming. Although this system was partially tested (both node command the actuator are operational) it was not used yet because the actuator needs special micro soldering that cannot be done without the right device.

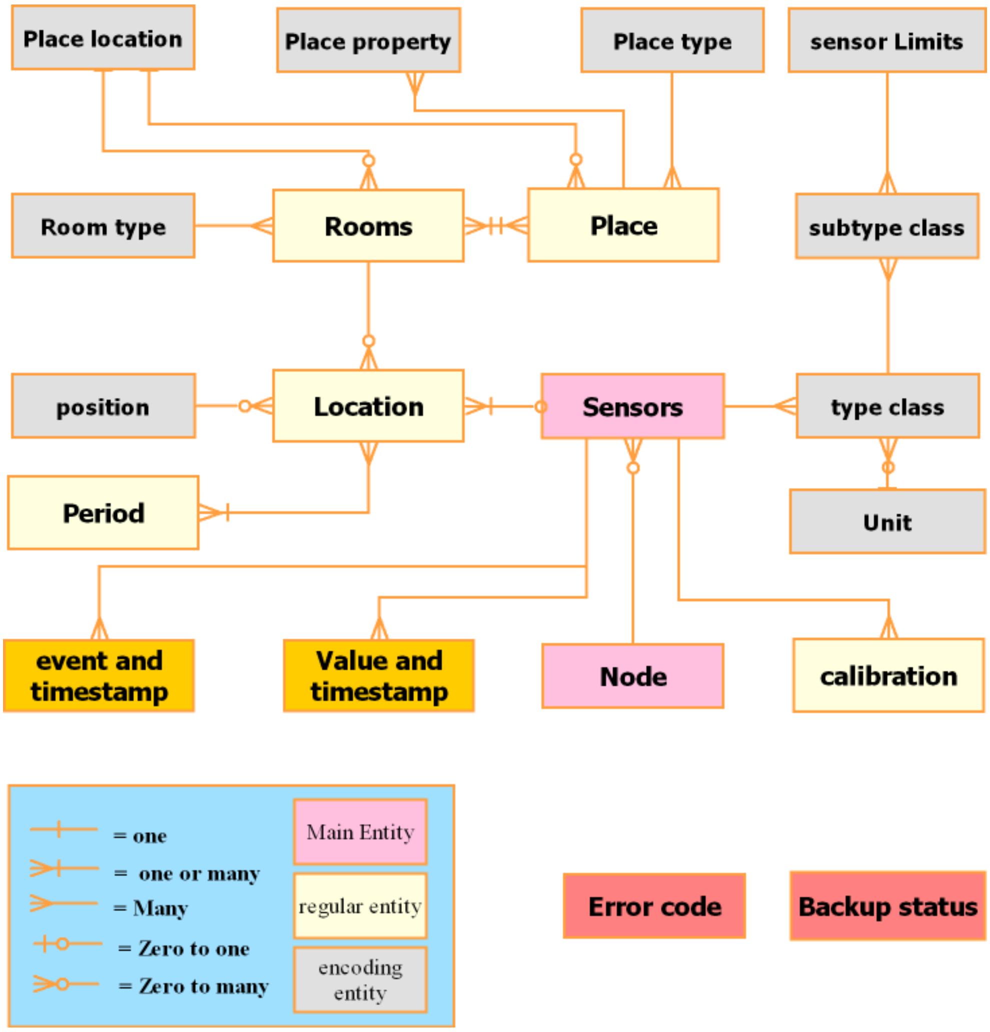


Figure 6.17 – DB's entity-relationship diagram

The gateway application, all developed in C++ code, actually is running without problems (that means at least one full week of continuous uptime) on a Pentium 3 notebook with 512 Mb RAM, a very cheap and common old computer nowadays.

On the same notebook, just described, can be executed at least two instances of the gateway application, one on each different virtual com port, together with a Nids application briefly described furthering this chapter.

In parallel to the WSN system, used for the first time, has been used the old gatherer system consisting in iButtons: button sized and shaped temperature and RH sensors with a five minutes sample rate. Their data were downloaded every two weeks (this is far to be a real time system) and reprogrammed with a three hour men cost. This system has proved to be much time costing and, when an error occurred, usually all the two weeks data were lost.

The database server was, also, designed to run on a common computer, in our specific case a Pentium 4 with one gigabyte of RAM (and Linux OS). The Database server chosen was the Postgresql 8 open source database, preferred to other open source DB like mysql due to its properties and flexibility (for instance mysql’s scripts, as reported in the user manual, can bypass the unique index check properties and also transactions have limits not found in postgres database) and its plsql script language very versatile.

The main entity-relationship diagram is illustrated in figure 6.17. Must be noted that to different tables exist that gather the measurements: one for the values such as temperatures or relative humidity, that can be described as a specific value in a specific moment, and one for events such us open/close door or window switches that have few states and last with the same state for long time. For these events, instead of generating thousands values all equals (i.e one thousand ON value for a door, one each five seconds) a single event with the value and the first and last timestamp was created into our table. Compared with 2,3 million data generated from switches less than two thousand rows were effectively created in our event table. The event management algorithm is aware of the possibility that many events can reach the DB in a different time and order respects the generation timestamp and is able to rearrange the events range accordingly to a unordered data flow. For a pre-configured period of time where no data are received on a switch state (the default is five minutes) an *UNKNOWN event status* is inserted reporting the period without data.

Although the creation of an events table has reduced the rows’ number in the measurements, the table itself has reached an over 20 millions records size exceeding the four gigabytes of space and very used indexes such as the pair sensor-timestamp values is now more than one gigabyte.

This situation has generated a significant performance degradation, for example a single record query (single value selection) has required more than 30 seconds to be performed on such database. Moreover these kind of query must be performed sometimes thousands times to satisfy the researches’ request (e.g. find two periods of at least one day with same external/internal condition one with HVAC running and one with HAVC turned off).

On of the main problems is due to the index size, the nearly two gigabytes were much over the 500 MB of RAM dedicated by the linux server to the database, thus any kind of tree search was impossible and the DB server performs a sequential read on disk at each request.

Moreover the postgres's clustering operation is a non dynamic process which means it works on the already stored value but it does not affect the new arriving values.

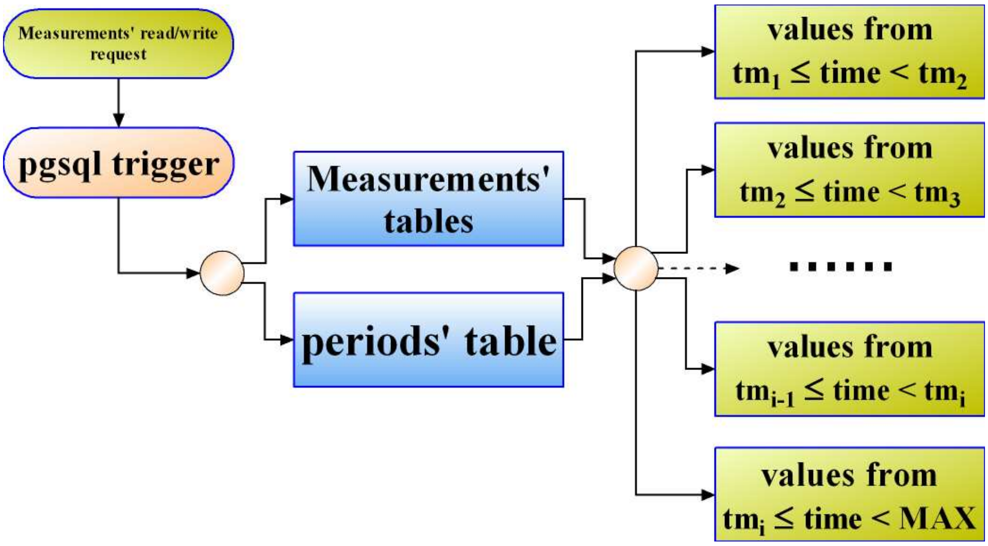
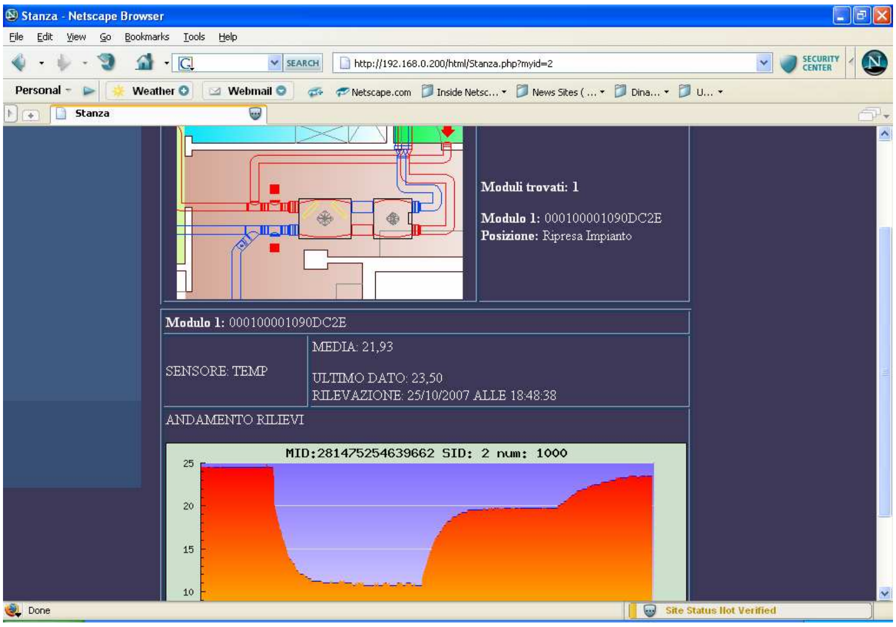

Measurements' read/write request
pgsql trigger
Measurements' tables
periods' table
values from $tm_1 \leq time < tm_2$
values from $tm_2 \leq time < tm_3$
......
values from $tm_{i-1} \leq time < tm_i$
values from $tm_i \leq time < MAX$

Figure 6.18 – pgsql trigger diagram

To improve the performance to a reasonable level the initial measurements table was divided into small tables (a dynamic cluster alike system) created by a pgsql trigger (postgresql script languages) rules based. The rows number of the tables is one of the script's parameter and must be calculated on the table final size desired. One of the values between the maximum flow rate and the maximum time range period must be specified to help the trigger to create tables that do not exceed the specified size. These values were introduced because sometimes, as explained before, the connection to the database is somehow interrupted (usually due to an adsl problem). In this case it may happen that a big volume of rows with an older timestamp (respect to the real time flow) arrives and, without any prevention mechanism, the results would be a table with a size greater than the requested limit.

The actual rows number is set at 750 thousands to achieve a final index size of about 64 Mb allowing the DB to perform tree scan over more tables simultaneously. The final performance reached is 0,5 seconds on a multi-table query (that is quite good considering the starting point of 30 seconds for a single table query).
The data are available, on real time (with usually less than two seconds of delay), through a web server apache on the same Linux OS computer where the DB is stored.
From this web server the researchers can view and download the required data in a format compatible with the most used tools (spss, matlab, excel).



Moduli trovati: 1

Modulo 1: 000100001090DC2E
Posizione: Ripresa Impianto

Modulo 1: 000100001090DC2E

SENSORE: TEMP

MEDIA: 21,93

ULTIMO DATO: 23,50
RILEVAZIONE: 25/10/2007 ALLE 18:48:38

ANDAMENTO RILIEVI

Figure 6.19 – a web site view
(from the real time demonstration of Bologna [MRB07])

The web site (access protected) is presented with a home page consisting of the house map where the user can click to access a room. For each room a sub-map is presented and the list of the found sensors. For each sensor is presented a summary with the day average value, the last value (and timestamp) and finally a graph with the last thousand values (with a rate of one measurements every 5 seconds this correspond at about 1,5 hours). By clicking on the graph or using the appropriate button a researcher can access the data download area. In figure 6.19 illustrates a web site page coming from the live demonstration of AICARR workshop in Bologna on 25/10/2007 (the temperature graph shows the results of a window opening).

6.2.2 Data analysis

Starting from September 2007 we stored in the database data about the following sensors ([MRB07] and [MRB08]):

- external air temperature and humidity conditions
- HAVC air temperature and humidity conditions before and after its heat exchanger
- Rooms air temperature and humidity conditions
- Bedrooms CO_2 conditions
- Windows and doors open/close state

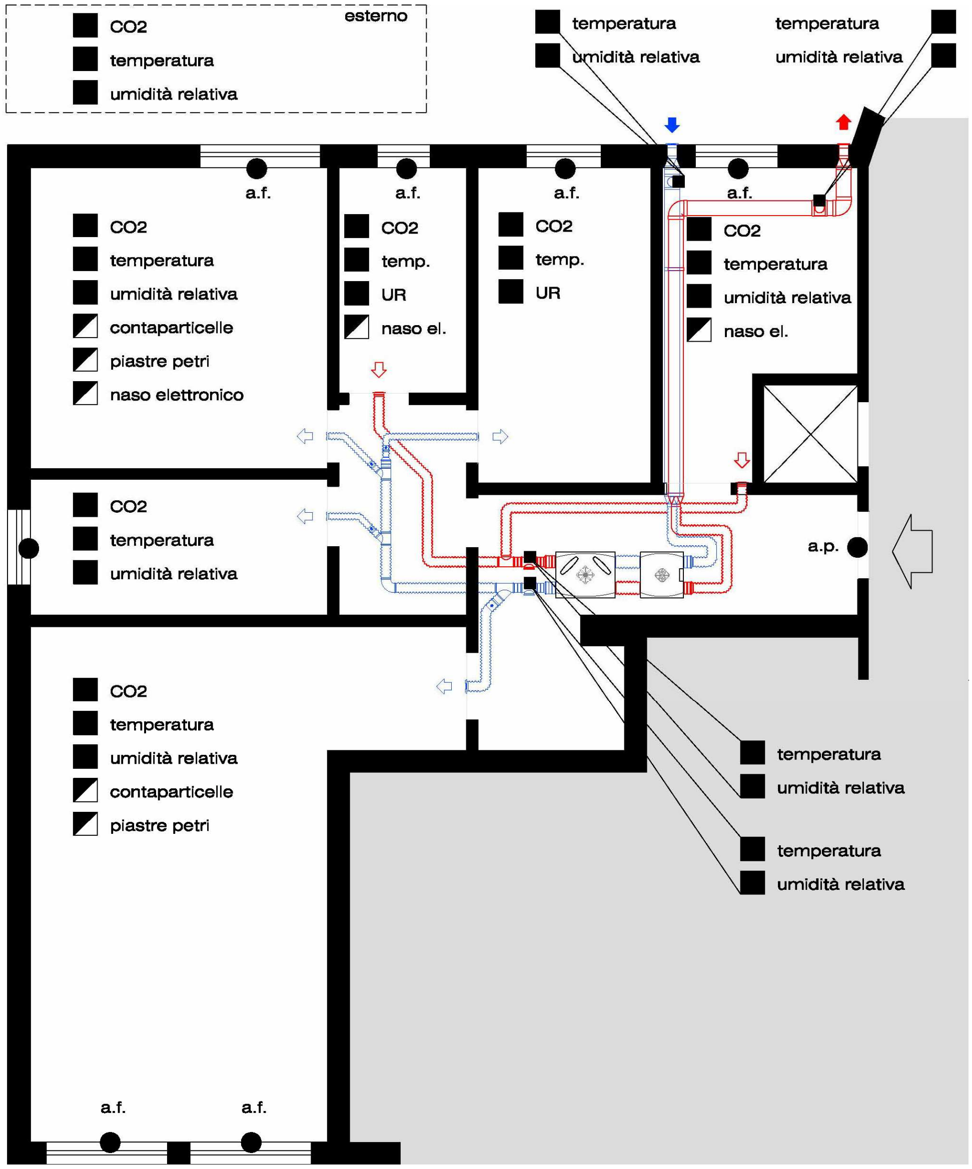


Figure 6.20 – House map with HVAC system

The HVAC system has an air flow 110 m^3/h which is equal to 0,4 house volume/h at 62 W of power consumption (speed 1 of 3).

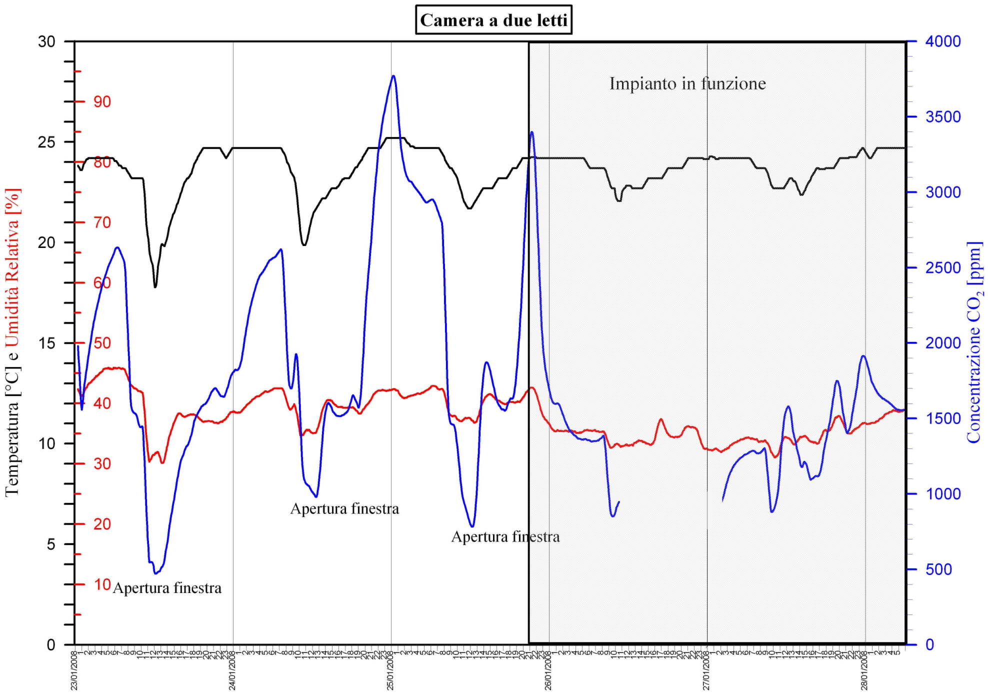


Figure 6.21– Bedroom Temperature, RH and CO2 conditions between 22.01.08 and 27.01.08

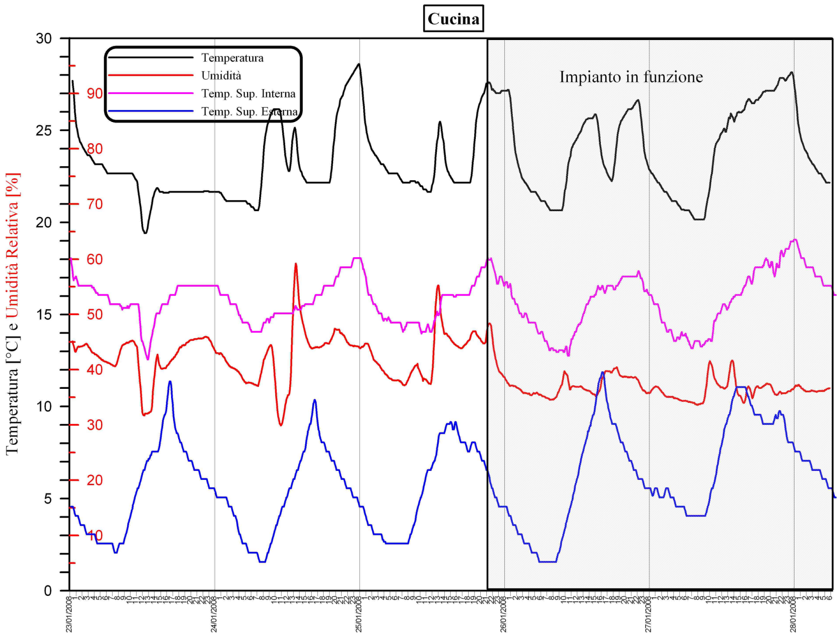


Figure 6.22 – Kitchen conditions (temp/RH) between 22.01.08 and 27.01.08

For more information about the HVAC properties and working condition see [MRB07] and [MRB08].

In figure 6.21 and 6.22 is shown an example of respectively the bedroom's and the kitchen's measurements stored in the database about a specific periods (respectively without and with HVAC running).

6.2.3 The efficiency of the HVAC heat exchanger.

Here is presented the efficiency of the heat exchanger calculated on the basis of the gathered data. The efficiency is calculated by:

$$\textbf{(5.1)} \qquad \eta_t = \frac{t_{22} - t_{21}}{t_{11} - t_{21}}$$

where:

- t_{11} is the average temperature of internal incoming air flow before the heat exchanger
- t_{21} is the average temperature of external incoming air flow (before heat exchanger)
- t_{22} is the average temperature of internal outgoing air flow past the heat exchanger

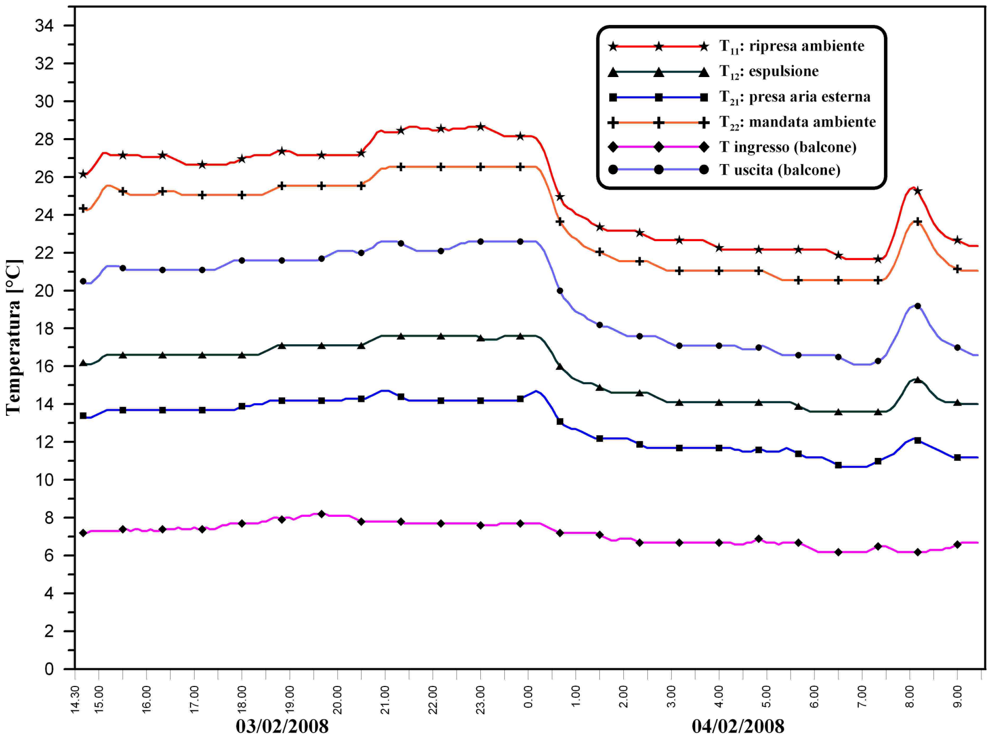


Figure 6.23 – Temperature measurements to calculate the HVAC efficiency

The data demonstrates that the heat exchanger efficiency is nearly the 90% as shown in figure 6.24

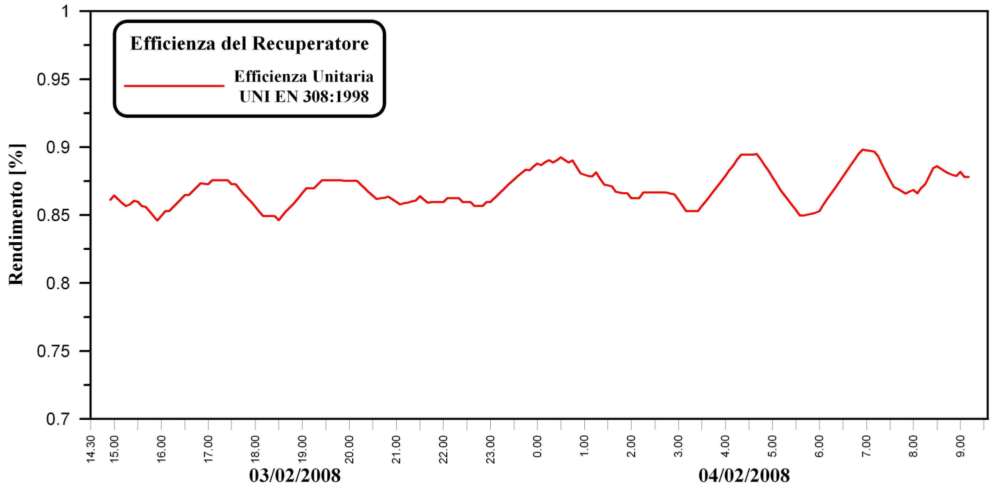


Figure 6.24 – HAVC's heat exchanger efficiency

6.2.4 Conclusion of the first on-field study

The first results analyzed are showing that mechanical ventilation plays an important role in limiting the CO_2 and humidity levels. The heat exchanger efficiency, referring at UNI EN 308/1998, reaches values of almost 90%.

Moreover, the data will be analyzed in relation to the habits of the inhabitants by monitoring also some parameters such as the state of the windows (opened or closed), the effective presence of people in the rooms and energy consumption of the dwelling in relation to the adopted ventilation systems (natural or mechanical).

The energy recovery is close to the theoretically value of 90% provided (by Aldes France) although Indoor Air Quality (IAQ) level (of inhabitants) can be improved.

6.3 On-field test application II

Aim of this second study was to demonstrate that between healthy subjects and subjects with Parkinson's disease and Ataxia objective detectable differences can be found in the average accelerations, obtained with an accelerometer, in strategic locations of the body, while they are walking at their comfortable speed.

Sixty-five subjects participated in the experiment (after giving their informed consent). For the age/disease distribution see table 5.1

Each subject, equipped with the accelerometer, was asked to walk in average three times (one for every experimental condition) at his more comfortable speed, a straight corridor 25 meters long. This distance permitted us to discard data from non-stabilized walk (beginning and end of walking test). In the first test the accelerometer was attached to the sternal region. In the second one it was attached in front of the sacral region. In the third, behind the sacral region (see figure 6.25).

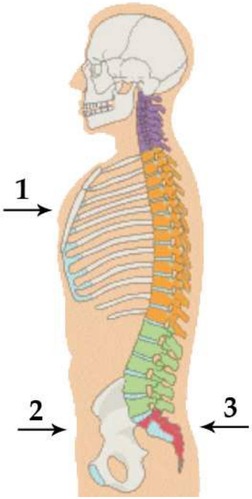


Figure 6.25 – Accelerometer positions

The mean acceleration value was calculated (at 20Hz sampling rate) via the following formula

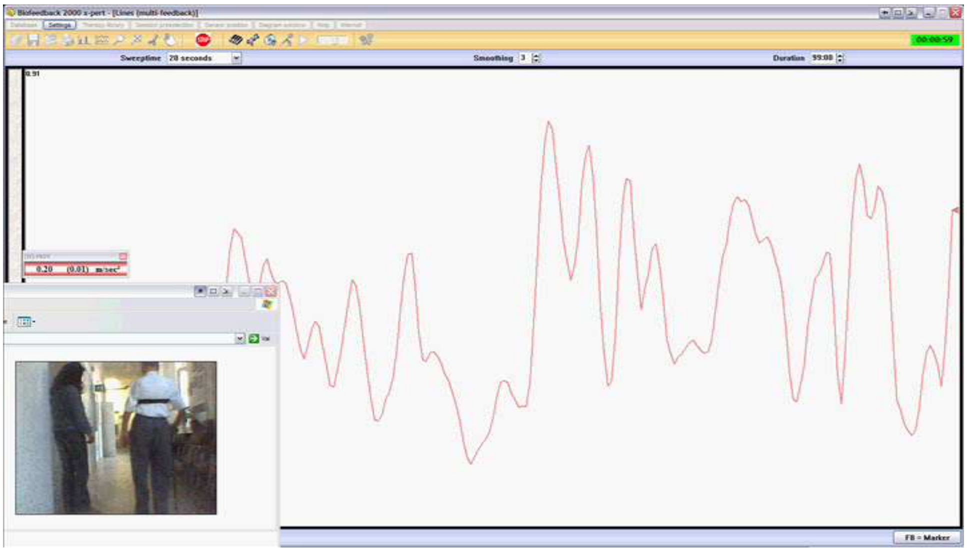
$$\textbf{(5.2)} \qquad \frac{0{,}05}{t_2 - t_1} \sum_{i=t_1}^{t_2} |a_i| \; {}^{m}\!/\!{}_{s^2}$$

	Age distribution:					
	20 - 39	**40 - 49**	**50 - 59**	**60 - 69**	**70 - 85**	Total:
Healthy subjects	8	6	4	3	3	24
Patients with Parkinson's disease	-	-	-	5	12	17
Ataxic patients	7	6	2	5	4	24

Table 6.2 – Age/disease distribution

6.3.1 The monitoring system

In the first period (late 2006 to early 2007) since the WSN system was not yet ready thus the monitoring system consisted of a Bluetooth device from a medical kit.



Sweeptime 20 seconds
Smoothing 3
Duration 99:00

Figure 6.26 – A patient test in progress

This device, with its triaxial piezoelectric accelerometer, was attached to the body with an elastic belt. The device had a sampling rate of 20 Hz so every 0.05 seconds it computed the arithmetic mean of the three axis acceleration and transmitted to the personal computer via a Bluetooth connection.

The main problem of such device is the interference produced by any other Bluetooth device (every time a mobile phone with Bluetooth activated were nearby the patient the connection between the medical device and the computer has fallen) and it's limited range.

Moreover the device itself although if has a tri-axial accelerometer it sends only the deviation from the arithmetic mean calculated over a time window. Due to such limitations the test was performed only at hospital.

The WSN system, with the same architecture shown in figure 6.12 and with the implemented compression illustrated in paragraph 5.6 can perform the task with a wider range of functionality.

For example, with the WSN system, the patient can be monitored at own home and over a long period to check how the movements change over time, how much and in which way the patient walk and if the trembling of the limbs are shown any kind of variation.

6.3.2 Conclusion of the second on-field study

With the technique used, based on the recording of the accelerations in the positions illustrated in figure 6.25, we found objective differences between healthy subjects, Ataxic patients and patients with Parkinson's disease (which show the lowest acceleration mean) [FGM08].

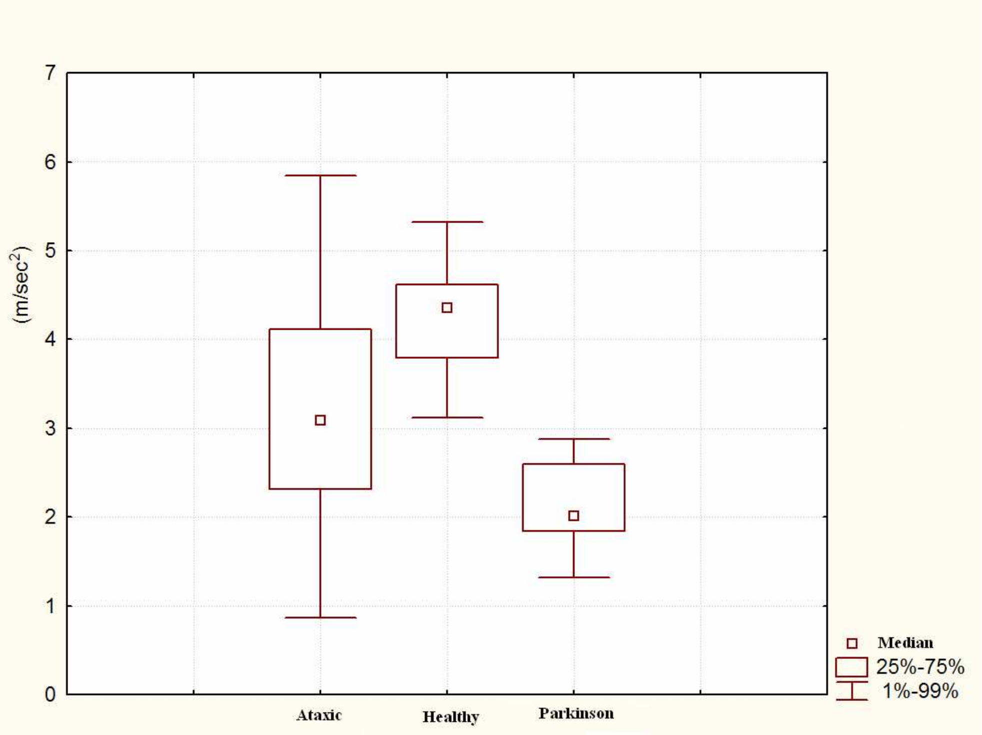


Figure 6.27 – Sum of the accelerations' mean of the three patient positions

Moreover, independently from the Type of Subject, the Frontal Sacral acceleration was always greater than the Back Sacral acceleration, that is greater than the one in the Sternal Region. The results suggest that triaxial accelerometry is a good tool for assessing the gait's alteration in PD and Ataxia. Moreover this assessment permits to obtain objective parameters in the evaluation of disease's progression and of therapy's efficacy. The WSN system data are still being analyzed.

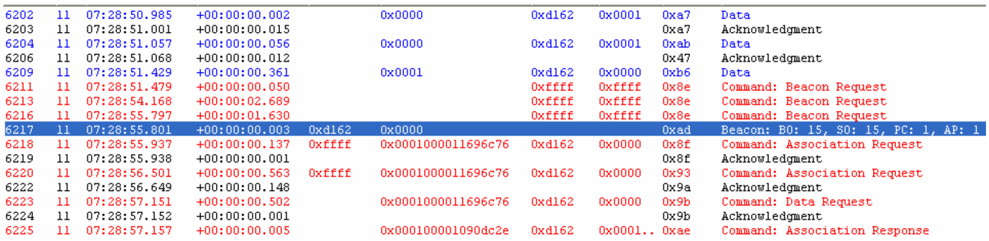
6.4 The Network intrusion detection system (NIDS)

The security of the WSN was another important aspect of the system and as noted in paragraph 4.5 there are many flaws in the ZigBee security mechanism.

The literature demonstrates an actual lack of Network Intrusion Detection Systems (NIDSs) although exist articles where we can find some proposition about a distributed intrusion detection systems for WSNs (i.e. [MaR07], [VBC06] and [Eid04]).

The described methods are too expensive in term of MCU calculation time and memory requirements to be implemented on our WSN (where we have about 10 kb free memory space and virtually no more stack space).

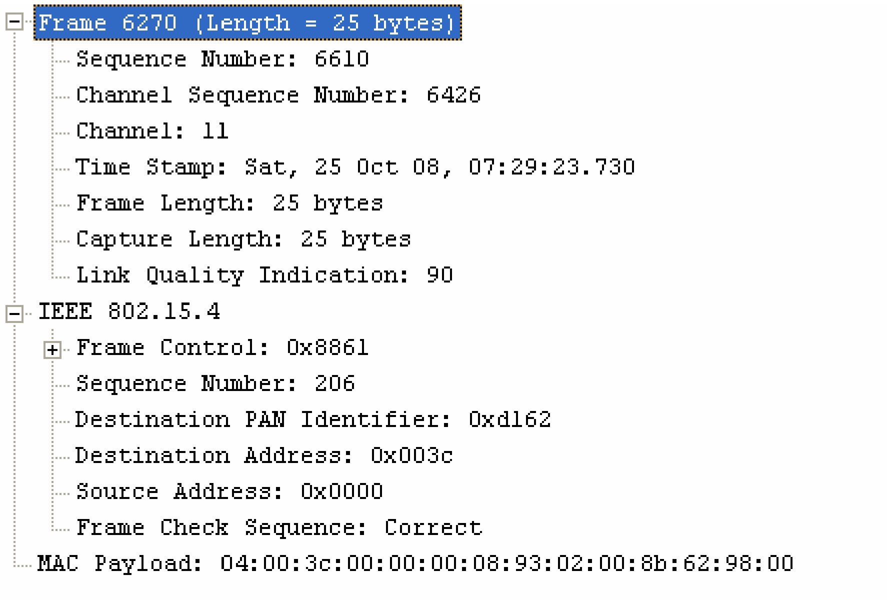
Moreover actually there aren't any specialized IDSs for WSNs or any wireless security systems with ZigBee packet analysis.



```
6202  11  07:28:50.985  +00:00:00.002          0x0000              0xd162  0x0001   0xa7  Data
6203  11  07:28:51.001  +00:00:00.015                                                0xa7  Acknowledgment
6204  11  07:28:51.057  +00:00:00.056          0x0000              0xd162  0x0001   0xab  Data
6206  11  07:28:51.068  +00:00:00.012                                                0x47  Acknowledgment
6209  11  07:28:51.429  +00:00:00.361          0x0001              0xd162  0x0000   0xb6  Data
6211  11  07:28:51.479  +00:00:00.050                              0xffff  0xffff   0x8e  Command: Beacon Request
6213  11  07:28:54.168  +00:00:02.689                              0xffff  0xffff   0x8e  Command: Beacon Request
6216  11  07:28:55.797  +00:00:01.630                              0xffff  0xffff   0x8e  Command: Beacon Request
6217  11  07:28:55.801  +00:00:00.003  0xd162  0x0000                                0xad  Beacon: BO: 15, SO: 15, PC: 1, AP: 1
6218  11  07:28:55.937  +00:00:00.137  0xffff  0x0001000011696c76  0xd162  0x0000   0x8f  Command: Association Request
6219  11  07:28:55.938  +00:00:00.001                                                0x8f  Acknowledgment
6220  11  07:28:56.501  +00:00:00.563  0xffff  0x0001000011696c76  0xd162  0x0000   0x93  Command: Association Request
6222  11  07:28:56.649  +00:00:00.148                                                0x9a  Acknowledgment
6223  11  07:28:57.151  +00:00:00.502          0x0001000011696c76  0xd162  0x0000   0x9b  Command: Data Request
6224  11  07:28:57.152  +00:00:00.001                                                0x9b  Acknowledgment
6225  11  07:28:57.157  +00:00:00.005          0x000100001090dc2e  0xd162  0x0001.. 0xae  Command: Association Response
```

Figure 6.28 – a packets' log

For these reasons was implemented a Nids using a sniffer device, a node that just read all packets and send it to the attached computer. The sniffer device is powered by both batteries and via an USB connection, so it can use more power to the signal antenna covering a larger area (in the first on-field test application, par. 6.2, it covers all the house). For a larger area, of course, we need more than one sniffer that gather data packets and send them to the same IDS.



```
Frame 6270 (Length = 25 bytes)
    Sequence Number: 6610
    Channel Sequence Number: 6426
    Channel: 11
    Time Stamp: Sat, 25 Oct 08, 07:29:23.730
    Frame Length: 25 bytes
    Capture Length: 25 bytes
    Link Quality Indication: 90
IEEE 802.15.4
    Frame Control: 0x8861
    Sequence Number: 206
    Destination PAN Identifier: 0xd162
    Destination Address: 0x003c
    Source Address: 0x0000
    Frame Check Sequence: Correct
MAC Payload: 04:00:3c:00:00:00:08:93:02:00:8b:62:98:00
```

Figure 6.29 – A decoded packet

As Nids was used Bro. Bro is a IDS developed as a research tool at the Lawrence Livermore National Laboratory [Pax99] used by the writer for his bachelor thesis [Gad01].
Bro provides high speed, large volume monitoring of the networks without dropping packets. It has a modular structure and it is easy to make distinction between different system modules. It is also easy to add new events, to the event engine, such as the ones coming from ZigBee packets.
There are three main layers in Bro:

- The *Packet Capture* Unit. It uses the libpcap library to capture packets from the network.
- The *Event Engine* analyzes packet streams captured by the Package Capture Unit, verifies their integration and sends them to the appropriate handler. Handlers are provided by the policy script interpreter.
- The *Policy Script Interpreter* runs scripts written in Bro language and associated with a handler. This script may execute other arbitrary commands to log events, modify state or record a data.

Bro is also designed to deal with attacks against itself such as overload attack , Crash attacks (using a watchdog) and subterfuge attacks.

The structure of the Capture Unit is specially made to isolates Bro from the underlying network technology and makes it portable and in our system the libpcap was substitute with a C++ library based on the pcap described in [Oks07] and [Gad01] designed to be connected on the USB port, instead of an Ethernet one, and the packet were decoded accordingly to the ZigBee packet structure illustrated in the previous chapters (see paragraphs 3.5, 3.6 and 4.3).

The event engine was expanded to generate the events accordingly to the new decoded packets, recognizing the overflow attempts and the replay attacks.

7

Conclusions and future works

This thesis is about the building of an efficient WSN system to be used in real indoor researches. The efforts were made towards the realization of a reliable yet flexible monitoring system easily capable of adapts to different scenarios. The WSN can be deployed in an inhabited place with the less visibility possible to avoid any kind of comfort reduction. Regardless of the results obtained much work is yet to be done.

7.1 Evaluation of results

The programmable WSNs, not specialized in a single task, are a relatively young area and the new specifications released in three different moments in the last years (ZigBee 2004, ZigBee 2006, ZigBee 2007 and PRO) demonstrate how the market is rapidly growing and its asking for more functionalities and security.

The ZigBee standard, as illustrated in this work, is made to a WSN with low data rate and very low power requirements and most of the development kits are designed just to demonstrate the WSNs can be useful, not to really realize projects.

The WSN system developed in this thesis, when used as a environment monitoring system, fits perfectly these properties, while the system applied in the second study needs a sustained data rate higher than the one the ZigBee is designed for.

The requirements of the second study does not completely fits neither the ZigBee WSN nor other wireless networks. On the other hand the WSN are the closest networks typologies answering to these needs.

The compression algorithm implemented into the WSN nodes demonstrates that it is possible to achieve even to tasks which are usually not directly allowed by the ZigBee but that are not so far from requirements.

Thus we can say that our system performs most of the tasks for which it was designed, with good disappearing properties. While the reliability and unattended capacity, although were greatly increased from since the starting situation, are not completely satisfactory and can be improved. In fact still persist the unexpected and random death of nodes, strongly decreased in number, because of causes that need a further investigation. A partial solution to this problem was created via a heartbeat system which create a more fault resilient system for the task that are considered particularly important. The heartbeat system developed was a simple way to create a backup node which can take the place of the dead node, without great sacrifices in power consumption, because the second device can use the sleep mode, and avoiding any data loss.

The modular library built to contain the sensor 'driver', with a common interface, help to increase the flexibility of our WSN application, allowing the swap or the link of a sensor without a node reprogramming but only via a new configuration command. Moreover this solution allows the developer to adapt the size of the library (and the number of sensor drivers) to the situation balancing the flexibility and the occupied resources.

However the lack of standards for the sensors communication is another limitation that is not expected to be solved in short periods, but as for the ZigBee standard, if a big manufacturer alliance, driven by WSN's market request, will propose a bus standard or will adopt one of the existent like the I^2C serial bus (hopefully with greater performance because of the new technologies available), then the situation could change.

A special attention was posed on the security issues which reveal several flaws due to the youth of the standard and the devices' few resources available. Nowadays, in fact, the security threats are taken in high consideration from both researchers and patients (or research's subjects), which are aware, at least, of the privacy's aspects involved.

Some procedures were implemented to solve the found security weakness and a network intrusion detection system (NIDS). In particular the packet capture library was substituted to adapt the NIDS itself to analyze the ZigBee traffic. The Nids was known by the author of this thesis since the 2000 and studied in his bachelor's degree thesis [Gad01].

This is just the first effort toward a WSN IDS as we may notice a lack in this security area while the first WSN malware is already available.

This NIDS, due to its resource requirements, run outside the WSN itself. In fact the MCU speed and the memory size of this second generation devices, almost completely occupied by the ZigBee stack library, greatly limit the expansion capabilities for these systems.

On the other hand the third generation devices, ready nowadays, seems finally solve this problem. Moreover also the bottleneck coming from the

virtual com port connection present on our nodes will be surpassed by the next generation chips (see paragraph 7.3.1 for more details).
So it is conceivable that with new technologies, the networks will also cover these needs and abilities, such as compression, will be implemented inside the standard layers.
A brief summary of the developed WSN system developed features can be seen in table 7.1.

	2006	**2009**
WSN		
node role chosen by switch	✓	✓
node role chosen by algorithm (dynamic)	✗	✓
Temperature sensor	✓	✓
Light sensor	✓	✓
RH sensor	✗	✓
CO_2 sensor	✗	✓
Tri-axial accelerometer sensor	✗	✓
Modular sensor code library	✗	✓
security flaws patches (anti syringe system)	✗	✓
power consumption management	✗	✓
cryptography	✓*	✓
crypto key protection	✗	✓
heartbeat system	✗	✓
data compression	✗	✓
data buffer	✗	✓
Gateway application		
multithread	✗	✓
COM reader	✗	✓
packet validation	✗	✓
sensors calibration values	✗	✓
node timeout check	✗	✓
nodes' command console (sends sensor config command)	✗	✓
Database connection	✗	✓
DB failsafe insertion	✗	✓

DB insertion when DB Server is on line	✗	✓
Error reports and logs	✗	✓
Database		
table split into dynamic sub-tables (cluster simulated)	✗	✓
Web interface		
remote access	✗	✓
monitor data in real time	✗	✓
download data	✗	✓
Criteria based data extraction	✗	✓

* flaws found

Table 7.1 – WSN system's features

7.2 Difficulties encountered

In this three year work many efforts were done to built a reliable system and many problems were found on the path.

One of the not completely solved problems are the 'dead nodes'. This problem was deeply investigated and many software bugs were patched, most of dead situation now cover periods of few minutes where the node memory buffer helps giving the possibilities to maintain the gather data. Most of the problems were due to the automatic behaviour of the library that was disabled, forcing an application redesign. Regardless there are still undiscovered death causes.

The main difficulty of this kind of problem, like most programming bugs, resides in the impossibility of a complete debug of the node application, that communicate only some status information via the three on board led. The programmer with debug capabilities helps only when the problem show no random properties and happens frequently (a node usually stops working after many hours).

The device power consumption was another painful aspect of our development. Most of the problems were caused by interrupt request, not managed, meanwhile the devices were in sleep mode. On the other hand the actual battery lifetime, although greatly increased (a router can last for a week instead of only two days) cannot be considered fully satisfying. This lifetime was increased to two weeks by using a bully algorithm that promotes the best node (regarding the battery charge) to be the router, while the other nodes use the sleep mode to preserve their energy (of course we are using the tree topology that allow this mode). The dynamic change between routers and end device implemented in our WSN help to achieve this task.

From the code programming development point of view the biggest problem was found on the *ATOMIC_SECTION* instruction that must be sometimes used to a single assignment statement to avoid unpredictable behaviours.

Also the implemented heartbeat system was a very difficult task to complete, many strategies were tested such as a distributed bully algorithm (that worked for the energy saving purpose) or a parent driven control. For many reasons the results were worse than expected and often the backup node did not succeed to the dead node. At last the beacon driven heartbeat system demonstrate to be the most efficient system.

Finally the few available resources (96kb of free code memory and 1kb of stack) were (and are) a real limit to the design of the system which force to a continuous application code profiling to avoid any kind of unexpected system crash.

7.3 Perspectives

A great number of indoor researches fields, requiring moderate data flows, can be completed using our WSN system with little application development efforts. Most of the work will be on adding new sensors into the library and in the web interface to adapt it to the application scenario.

One of the studies, we want carry out, that cannot be achieved yet by our WSN system is the mental disease monitoring system to research mental disorders at electroencephalography (EEG) level to foresee, via objective measurements, abnormal behaviours.

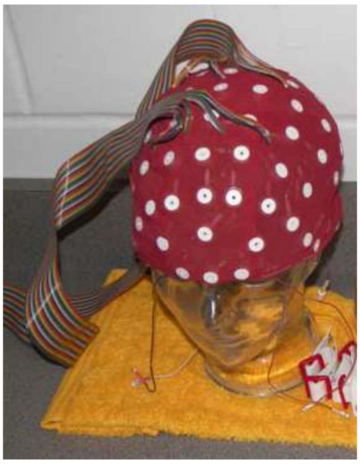


Figure 7.1 – an EEG sensors' cap

The EEG (32 or 48 lines 240hz minimum sampling rate) sensors' cap produces a data flow that is not sustainable by our second generation devices. On the other hand, the new generation nodes can probably perform the data gathering, but to complete the task a deep analysis of pattern recognition algorithm, regarding their memory and computing resource requirement, must be performed. This analysis can be done only when a knowledge discovery phase applied on the gathered data will be completed.

7.3.1 MCU Evolution (the third generation devices)

The AVR ATMega MCU provided with our second generation kit is a 8 bit device with 256Kb Flash memory and a 4 Mhz clock and 4 Mips (but can reach 8 Mhz and 8 Mips) and 4 KB sram. The new MCU series are divided in two different categories: for very power consumption applications or for performance applications, but also in the last case the power consumption is less or equal to the second generation MCU. Actually we can find chips that reach 66 Mhz of clock speed and capable of more than 70 Mips (16/32 bit architecture) 512 Kb (but there are MCU with 1 or 2 Mb), Real usb 2.0 (12Mbps) and/or full Ethernet connection.

Most MCU now offer an event engine support, DMA channels and controllers, crypto engine (DES and AES) and are designed to be more secure.

This is a clear sign of how manufacturers are responding to the market requests.

7.4 Open problems

One of the main open problems for the WSNs is the minimization of the orphan problem. Every time a node cannot join the network, not because is out of the range of any router but because the close routers have already reached their maximum number of children then that node is called an orphan. Our system does not suffer for this problem only because the reduced number of nodes connected.

But in a WSNs where a large deployment of nodes is realized this effect is highly visible. For example in [Pat07] over 3 thousands node, with eight hundred router, where randomly deployed. The results using the ZigBee address assignment first stage algorithm lost about 25% of devices that will become orphan nodes (see figure 7.2).

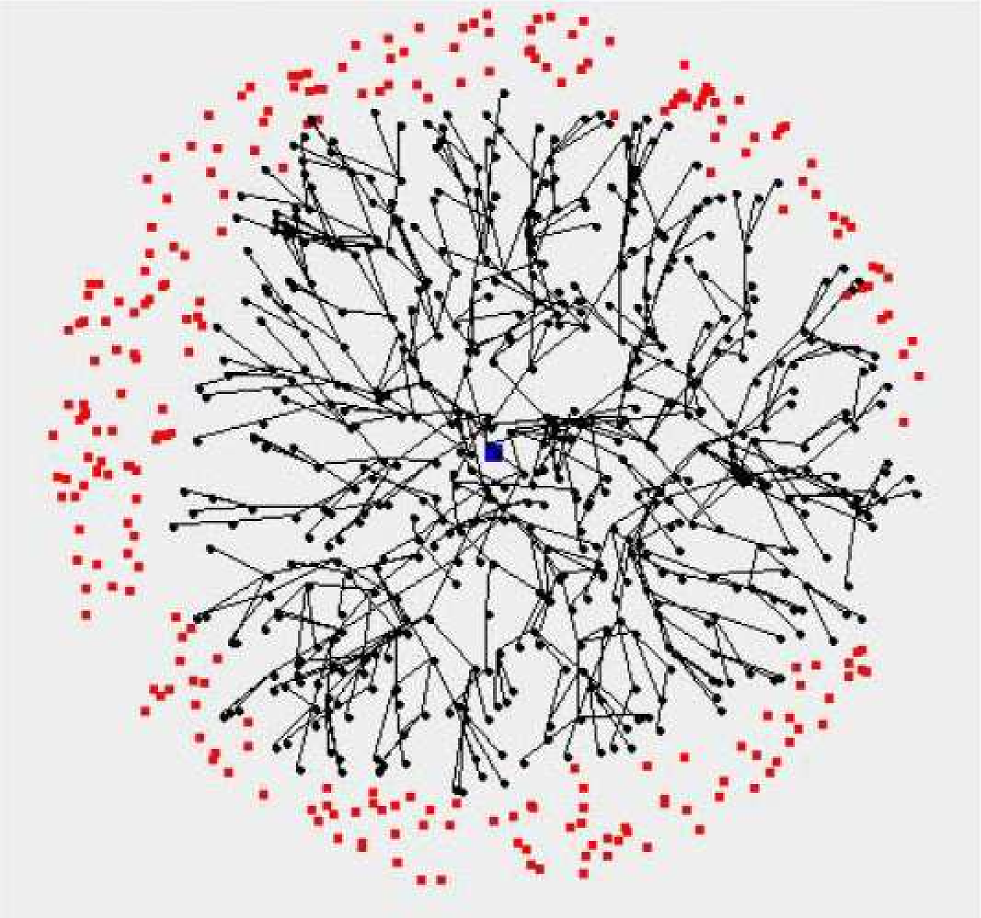


Figure 7.2 - Network formation results by ZigBee [Pat07] (red points are the orphan nodes)

Another great step for this WSN, would be the distributed pattern recognition that can greatly help a single device to achieve a computing exhausting task to be performed with the help of other idle nodes.
The main problem to achieve this task is to manage the set of node that tend to change over time, due to very different (and often) unpredictable reasons, without notice.

The last improvements is a distributed WSN NIDS as described in [MaR07]. Its implementation as many difficult aspects regarding how a node can be considered suspect. Moreover, although some type of attacks can be easily recognized (e.g. replay attacks see appendix A for more information) an event engine like the one used in our external NIDS (Bro) may be needed for the stealth type attacks and the malware.

All the three improvements described have high cost in term of design time and resource requirement and they can easily cover a study period equal of the one just described in this thesis.

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A.

Security attacks and attackers

Different types of attacks

Security attacks can be classified into two classes: passive and active attacks. Passive attacks, where intruders do not make any emissions, are usually against data confidentiality while, in active attacks, malicious acts are not only against data confidentiality but also data integrity.

Active attacks can also aim for unauthorized access and resources usage or the block of an opponent's communications. An active attack makes an emission or action that can be detected.

Apart from security attacks security threats can also come by mistakes. The WSN's nodes can be exposed to tampering and destruction, and classified data and resources can be categorized as unauthorized access.

Passive Attacks

Must be notes that RF is not the only wireless medium used. There are several wireless carriers, such as infrared, which are more resilient to attacks because these kinds of channel are usually directed and spatially limited.

To intercept them, the intruder's receiver needs to be located accordingly, which makes the adversary's goal more difficult and the possibility that to be detected higher

In passive attacks attackers are usually camouflaged (hidden, disguise) and tap the communications to collect data. Passive attacks can be grouped into eavesdropping and traffic analysis types.

Eavesdropping

Data can be eavesdropped by intercepting communications, and wireless links are easier to tap, so wireless networks are more susceptible to these kind of attacks. We can consider a situation where known standards are used and plain data, which is not encrypted, it is sent wirelessly. In fact, in this case, an adversary can easily receive and read the data

WSNs are more secure against eavesdropping than to other longer range wireless technologies because signals are sent over shorter distances.

An intruder needs to get close enough to the attacked node to be able to intercept the signals. If the facility where these wireless technologies are used has enough space controlled against intruders it becomes more secure. However, they can never become as secure as wired communications.

An attacker close enough to a device can receive all frames to or from it, store them in some medium and take them out of the facility.

Moreover, the existence of wireless communications makes the implementation of multiple networks with different security levels much more difficult. For instance, if there are a classified networks and a network attached to the Internet in the same facility and wireless access to the classified networks is allowed, the splitting of the Internet and the classified networks can become very difficult due to passive attacks and mistakes/misjudgements.

Must also be noted that is a difference between privacy and confidentiality. Environments enabled by wireless ad hoc and sensor networks may be forced in order to access not only confidential data but also private information. For instance, the security system cameras may be attacked passively to observe the private lives of others.

Analysis of data may also lead to private information, therefore, some information not considered confidential at first sight may be private and should be protected.

Traffic Analysis

As well as the data packets content, the traffic pattern may also be very valuable for intruders.

For example, important information about the networking topology can be derived by analyzing traffic patterns.

In sensor networks, the nodes closer to the base station such as the sink, have more transmissions than the other nodes because they relay more packets than the nodes farther from the base station.

Similarly, clustering is important for scalability and cluster heads are busier than the other nodes in the network.

The detection of the sink, the nodes near to it or cluster heads may be very useful for adversaries because a denial-of-service (DoS) attack against these nodes or eavesdropping the packets have a greater impact.

By analyzing the traffic, this kind of valuable information can be derived.

Traffic analysis can also be used to project attacks against anonymity. Detecting the source nodes for certain data packets may also be a target for intruders. This information helps to localize weaknesses, capabilities and the functions of the nodes.

Moreover, traffic patterns can concern to confidential information such as actions and intentions.

In tactical communications, silence may indicate preparation for an attack, a tactical move or infiltration, while a sudden increase in the traffic rate may indicate the start of an attack.

Similar information can also be derived by traffic analysis in civilian networks. One of the following techniques may be used for traffic analysis:

- *Traffic analysis at the physical layer*: in this attack only the carrier is sensed and traffic rates of the nodes are analyzed.
- *Traffic analysis in MAC and higher layers*: MAC frames and data packets can be demultiplexed and headers can be analyzed. This can reveal the routing information and the network topology.
- *Traffic analysis by event correlation*: events like detection in a WSN or transmission by an end user can be correlated with the traffic and detailed information, such as routes, can be derived.
- *Active traffic analysis*: traffic analysis can be conducted as an active attack. For instance, a certain number of nodes can be destroyed, stimulating the self reorganization of the network gathering in this way valuables information about topology.

Active Attacks

In active attacks an intruder actually affects the operations in the attacked WSN. This effect may be the goal of the attack itself and can be detected. For instance, some services may be degraded or terminated as a result of these attacks.

Sometimes the intruder tries to stay undetected, aiming to gain unauthorized access to the system resources or threatening confidentiality and/or integrity of the content of the network.

We classify active attacks into four different classes, as illustrated in figure 3.23

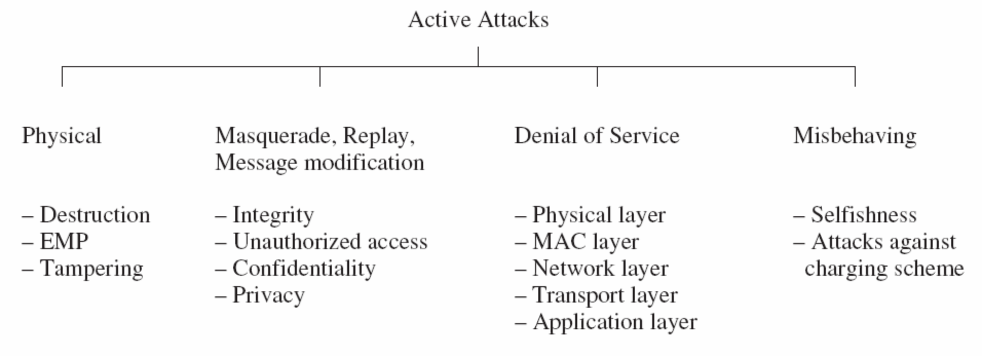


Figure A.1 - Active attacks

Physical Attacks

An intruder may damage hardware to destroy the nodes. This is a security attack that can also be considered to fall in the domain of fault tolerance (the ability to sustain networking functionalities without any interruption due to node failures).

Physical attacks may become a serious issue, especially in sensor networks, sensor nodes, indeed, may be positioned in unattended regions accessible by external people. Therefore, they can be moved out of the sensor field to access the inside information or damaged.

When we must avoid these risks we have to use nodes resilient to physical attacks.

Node tampering can help in masquerading a DOS attacks, explained further in this chapter. Tamper resilience is an issue that needs to be considered carefully in many sensor network, although it can be very expensive to achieve.

We can group tampering into two classes: invasive and non invasive tampering.

Invasive techniques aim to gain unlimited access to a node. In non invasive attacks, unlimited access to the node is not the intention. Instead, by analyzing the behaviour of a node, such as the power consumption, or the execution timings of the algorithms for various inputs, confidential data about the procedures and keys used by the encryption schemes can be derived.

Electromagnetic pulse (EMP) can also be listed within physical security attacks. An EMP is a short-duration burst of high-intensity electromagnetic energy. It can produce voltage surges damaging electronic devices within its range.

Although today are available portable devices that can generate EMPs, there are still unsolved issues related to the practicability of these attacks because of their threat for all kinds of electrical devices, not only for WSN’s nodes.

This can be considered, again, as part of the fault tolerance domain and it is possible to build nodes that are more resilient to EMPs.

Masquerade, Replay and Message Modification

A masquerading device acts like if it would be. Messages can be captured and replayed by masquerading nodes and in addiction the content of the captured messages can be modified before being relayed.

Ad hoc and sensor networks introduce particular advantages for masquerading techniques. In mobile ad hoc networks, nodes may change their location in the network. This location is not given or fixed, and self-forming and self-healing mechanisms are counted on to adapt to topology changes. It may be difficult to check the consistency of a node's access point to the network since the reactive techniques are preferred to the control ones due to network's topology.

Sensor networks are even easier in terms of masquerading because global identifications is not used in sensor networks.

Masquerading, message replay and content modification can be used to attack the integrity of the content of messages or even a service in a network. Sensor networks in particular have several network functions susceptible to security attack because they are based on a collaborative effort of many nodes. For instance, node localization schemes may be subject to one of the following security attacks:

- A malicious node may act as a beacon and disseminate its location wrongly. This is an obstacles to node localization procedure when the node uses beacon signals transmitted by the malicious node for triangulation.
- A beacon may be tampered with and introduce wrong location data, or slightly desynchronize the RF transmission.
- Beacon signals may be replayed by a malicious node.
- Beacon nodes may be destroyed by physical attacks.
- An obstacle may be placed between nodes to block the direct line of sight.

There are many more attack and in addition to node localization schemes, the integrity of the following services may also be subject to similar attacks:

- Data aggregation and fusion make WSNs more sensitive to replay and content modification attacks because changing the content of message may change the data provided by several nodes.
- Time synchronization is also a vulnerable service. Several insiders that inject false synchronization's messages may prevent the system from achieving time synchronization. Time synchronization can be very sensitive to replay attacks. A malicious node can jam a time synchronization message at a certain part of a network, and then replay the message at that part after a very short delay. This may prevent correct time synchronization and create many problems on all services that rely on the accuracy of the synchronization protocol.
- Data correlation and association techniques are also compromised when node localization or time synchronization services are attacked.

- Modifying the contents of the messages, event and event boundary detection algorithms can be hampered.
- Node management systems can be blocked by modifying the messages that report node status or commands for node management.

An improved version of masquerading is a *Sybil* attack, where a malicious node introduces itself as multiple nodes. Having multiple identifications can be very useful for a malicious node.

For instance, a Sybil attack can be brought against data correlation and aggregation algorithms. A node that sends multiple values with different identifications can change an aggregated value considerably. A Sybil attack can also take control of multiple path routing, and similarly to node localization, and several other services. Multiple identifications also help to keep the attacks hidden.

Must be noted that we can also consider attacks against the integrity of services as DoS attacks (explained later in this paragraph) because they reduce the availability of some services.

Message replay, content modification and masquerading attacks can also be used against confidentiality by making the other nodes send the confidential data to a malicious node or by accessing the confidential data directly.

Finally they can be used for gaining unauthorized access to system resources via *phishing* techniques, which means deceiving someone in order to make him/her give confidential information voluntarily (phishing is a combination of the words *password* and *fishing* which defines this attack well).

Denial-of-Service Attacks

A denial-of-service (DoS) attack mainly targets the availability of network services and is defined as any event that diminishes a network’s capacity to perform its functions correctly. A DoS attack is characterized by the following properties [WSJ05]:

- **Malicious** when it prevent the network from fulfilling its expected functions. It is not accidental, otherwise it is not in the domain of security but reliability and fault tolerance.
- **Disruptive** if it degrades the quality of services offered by the network.
- **Asymmetric**: the adversary puts in much less effort compared to the scale of the impact made on the network.

Every networking service may be subject to a DoS attack and now the most important DoS scenarios will be briefly illustrated for ad hoc and sensor networks.

DoS in The Physical Layer

All physical attacks previously illustrated can also be considered as DoS attacks because they prevent a network from performing its expected functions.

In this section, the physical layer indicates the OSI layer responsible for representing 1s and 0s correctly in the wireless medium, and a DoS attack in the physical layer, which is called jamming, means a security threat against this.

An attacker device can jam a wireless carrier by transmitting a signal at that frequency. The jamming signal contributes to the noise in the carrier and its strength is enough to prevent the nodes to receive data correctly.

Jamming can be conducted continuously in a region but also temporarily with random time intervals, both methods are usually very effectively.

DoS in The Link Layer

The algorithms in the link and MAC layers schemes, present many opportunities for DoS attacks. For instance, MAC layer DoS attacks such as one the following may completely and continuously jam a channel [WSJ05]:

- Whenever an RTS signal is received by the malicious device, a signal that collides with the **CTS signal is transmitted**. Since the nodes cannot start transmitting data before receiving the CTS, they continue sending RTS signals.
- If the MAC scheme is based on sleeping and active periods (using beacons), jamming only the active periods can continuously block the channel.
- **False RTS or CTS** signals with very long data transmission parameters are continuously sent out, which makes the other nodes wait forever.
- Acknowledgement spoofing, where an intruder sends false link layer acknowledgements for overheard packets addressed to neighbouring nodes, can also be a very effective link layer DoS attack.
- **Spoofed, altered or replayed routing information**: routing information exchanged in the WSN can be altered by malicious devices to have a worsening effect on the routing capability.

- **Hello flood attack** [KaW03]: an attacker device may broadcast routing or other information with high enough transmission power to convince every node in the network that it is their neighbour. When the other nodes send their packets to the malicious node, those packets are not received by any node (Figure 3.24).

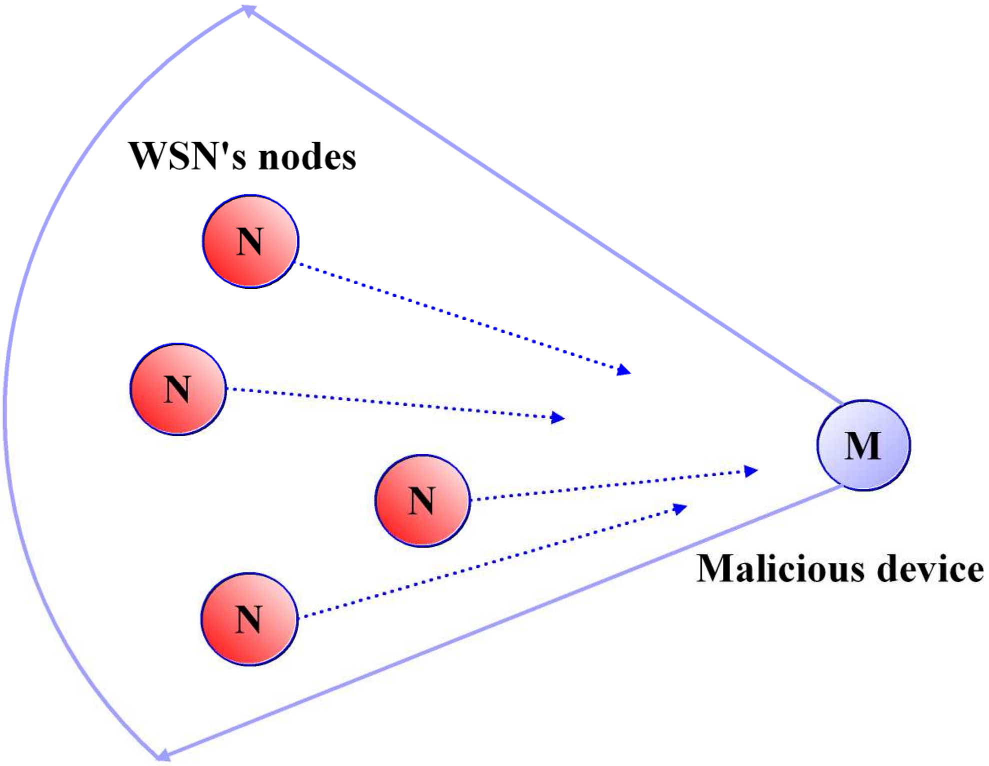


Figure A.2 - Hello flood attack

- **Wormhole attack**: a malicious device can eavesdrop or receive data packets and transfer them to another malicious node, which is at another part of the network, through an out-of-band channel. The second malicious node then replays the packets. This makes all the WSN's nodes that can hear the messages by the second malicious device believe that the node that sent the packets to the first malicious node is their single-hop neighbour and they are receiving the packets directly from it. For instance, the packets sent by node a shown in Figure 3.25 are also received by node w1, which is a malicious device. Then node w1 forwards these packets to node w2 through a channel which is out of band for all the nodes in the network except for the intruders. Node w2 replays the packets and node f receives them as if it was receiving them directly from node a. The packets that follow the normal route, such as a to f, reach node f later than those conveyed through the wormhole and are therefore dropped because they do more hops. Wormholes attacks are usually established through faster channels. Wormholes are very difficult to detect and can dramatically impact on the performance of many network services such as time synchronization, localization and data fusion.

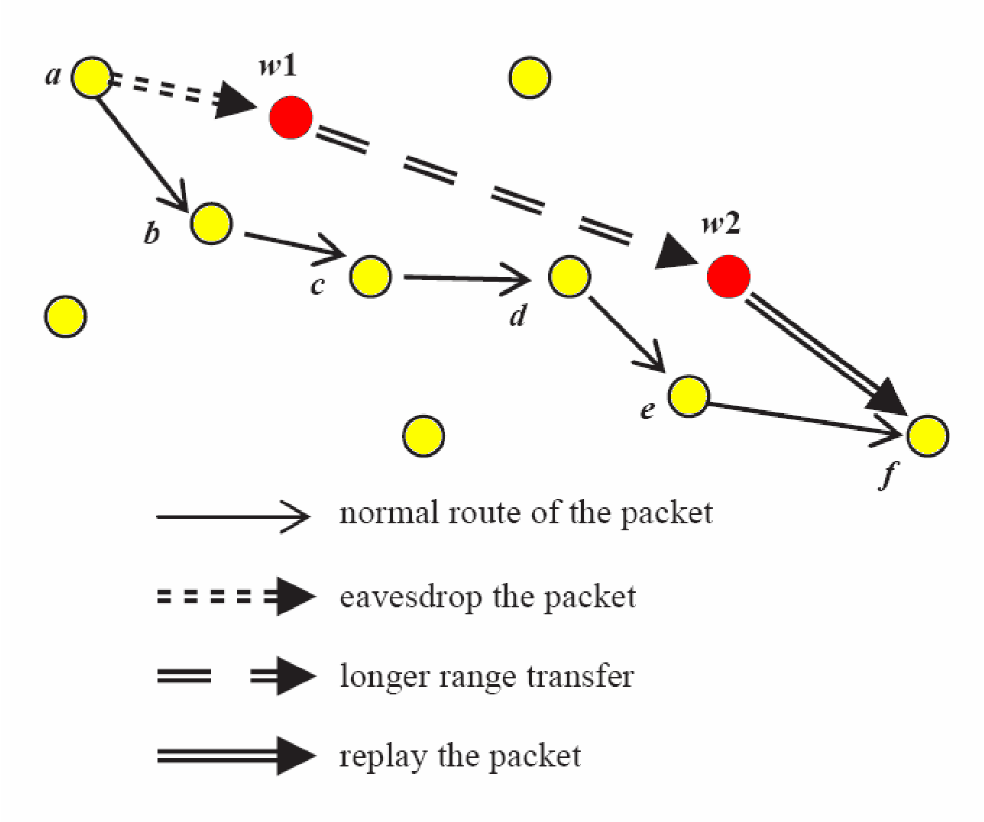


Figure A.3 - Wormhole attack

- **Detour attack**: an adversary may attempt to detour traffic to a sub optimal route or to partition the network. Various techniques can achieve this goal. For example, [HYP05] define a gratuitous detour attack, where a device on a route adds virtual nodes to the route.
- **Neighbour attack**: An intermediate node usually, upon receiving a packet, records its ID in the packet before forwarding the packet to the next node. An attacker, however, simply forwards the packet without recording its ID in the packet to make two nodes that are not

within the communication range of each other believe that they are neighbours. The result is a disrupted route

- **Sink hole attacks**: a malicious device can be made very attractive to the closed nodes with respect to the routing algorithm. For instance, attractive routing advertisements can be broadcast and all the neighbouring nodes can be convinced that the malicious device is the best next hop for sending the packets to the base station. When a node becomes a *sink hole*, it becomes the hub for its vicinity and starts receiving all the packets going to the base station.
- **Black hole attack**: a malicious node may drop all the packets that it receives for forwarding. A blackhole attacker first needs to invade a multicast forwarding group, for instance, by implementing rushing attack, in order to intercept the multicast session data packet. Then drops some or all data packets it receives instead of forwarding them to the next node on the routing path. This type of attack often results in very low packet delivery ratio. This attack is also very effective when the black hole node is also a sink hole. Such a combination may stop all the data traffic around the black hole.
- **Selective forwarding** (*gray hole attack*): when a malicious node drops all the packets, this may be detected easily by its neighbours. Therefore, it may drop only selected packets and forward the others.
- **Routing loop attack**: detour or sink hole types of attack can be used to create routing loops to consume energy and bandwidth as well as disrupting the routing.
- **Sybil attack**(also classified as a masquerade attack): a single node presents multiple identities to the other nodes in the network. This reduces the effectiveness of fault-tolerance schemes and poses a significant threat to geographic routing protocols. See paragraph 3.7.2.2 for more information.
- **Rushing attack** [HYP05]: an attacker disseminates route request and reply messages quickly throughout the network. This suppresses any later legitimate route request messages, i.e. nodes drop them, because nodes suppress the other copies of a route request that they have already processed. ZigBee protocols use a form of duplicate suppression in their operations, and this behaviour is vulnerable to rushing attacks. When source nodes flood the network with route discovery packets in order to find routes to the destinations, each intermediate node processes only the first non-duplicate packet and discards any duplicate packets that arrive at a later time. A rushing attacker exploits this duplicate suppression mechanism by quickly forwarding route discovery packets in order to gain access to the forwarding group.

- **Attacks that exploit node-penalizing schemes**: schemes that avoid low performance nodes can be exploited by intruders. For example, malicious devices can report error messages for a node which is actually performing well. Therefore, the routing scheme may avoid it using a route that includes this node. Similarly, a link may be jammed for a short time but since error messages are generated about the link during that time interval, the routing scheme may continue to avoid the link even though it is not jammed any more.
- **Attacks to deplete network resources**: when devices are unattended and rely on their onboard resources, those resources may be depleted by malicious actions. This is especially the case for sensor networks. For instance, a malicious node may continuously generate packets to be sent to the data-collecting node and the nodes that relay these messages will deplete their energy rapidly.
- **Jellyfish attack**: A jellyfish attacker first needs to intrude into the multicast forwarding group. Then, it delays data packets unnecessarily for some amount of time before forwarding them. This results in significantly high end-to-end delay and thus degrades the performance of real-time applications

DoS in The Transport Layer

Transport layer is also susceptible to security attacks. Some attack scenarios are described below:

- **Transport layer acknowledgement spoofing**: false acknowledgement or acknowledgement with large receiver windows may make the source node generate more segments than the network can handle, causing congestion and degrading the network performance.
- **Replaying acknowledgement**: in some transport layer protocols, acknowledging the same segment multiple times indicates negative acknowledgement. A malicious device can replay an acknowledgement multiple times to make the source node believe that the message was not delivered successfully.
- **Jamming acknowledgements**: a malicious device can jam the segments that convey acknowledgements. This bring to the connection’s termination
- **Changing sequence number**: in many protocols, a malicious node may change the sequence number of a fragment simulating the loss of some fragments.

- **Connection request spoofing**: a malicious device can send many connection requests to a node, using up its resources such that it cannot accept any other connection request.

Attackers

Attackers can also be classified according to several criteria.

The following classification of attackers is based on the characteristics shown in Figure 3.30: emission, location, quantity, motivation, rationality and mobility.

First, an intruder can be passive or active; matching the attacks' classification. Active attacks are carried out by active attackers and passive attacks by passive attackers.

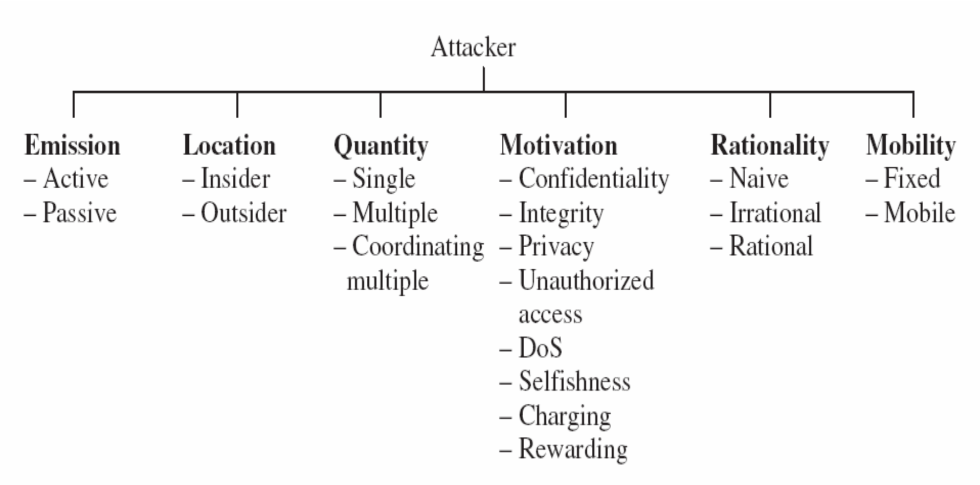


Figure A.4 - Classification of attackers

An attacker can be an insider or an outsider. An insider is a device that has been compromised, and it is a part of the attacked network.

The attacker knows all the cryptographic information owned by the compromised device when it is an insider.

Outsider attacks can be either passive or active. Moreover, an insider can be perceived as a legal entity inside the network such as a node that is allowed to join the network. Instead, an outsider is typically a device that is not welcome to access the network.

The attacker can be a single entity or more than one. When there are multiple attackers, they can collaborate with each other, which can be considered a more difficult case to defend against.

In [HYP05] active attackers are denoted as Active-n-m, where n is the number of insider nodes, and m is the total number of insider and outsider nodes. They then propose an attacker hierarchy with increasing strength as follows:

- **Active-0-1**: the attacker owns only one outsider node.
- **Active-0-x**: the attacker owns x outsider nodes.
- **Active-1-x**: the attacker owns x nodes and only one of them is an insider.
- **Active-y-x**: the attacker owns x nodes and y of them are insiders.

Must be noted that in this hierarchy all the nodes represent a single attacker. Therefore, they are supposed to collaborate. An attacker usually have motivations to act against the network, such as breaking confidentiality, integrity and privacy.

This may also be done to gain access to unauthorized resources. An attacker may also attack to hinder the operations of the other side.

Selfishness, avoiding payment or getting unearned rewards may be other motives.

However, an attacker may attack simply in order to attack and break a security system, perceiving this as a challenge.

Rational attackers carry out their attacks to obtain something which is more valuable than the cost of the attack.

Finally, adversary can be fixed or mobile. Detecting mobile attackers and defending against them is usually more difficult than defending against a fixed adversary

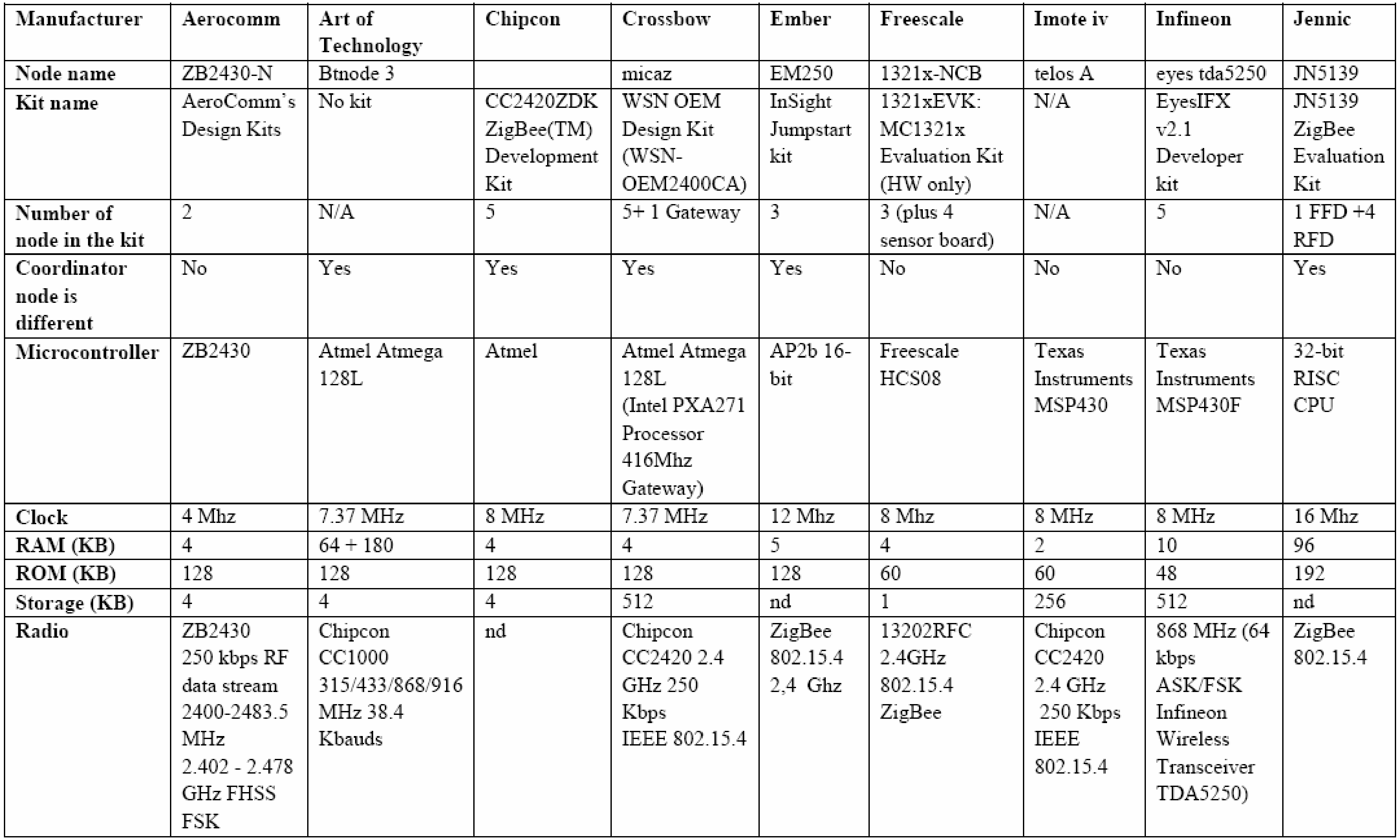
B.

Development kits and Meshnetics 'how to' guide

In this appendix is shown the summary of the synoptic table used to analyze the available kits, at the beginning of our work.

In the table are presented only the main characteristics of the kits and must be underlined that the prices reported are to be intended as indicative and strictly linked to the periods the kits were analyzed (at the beginning of this work).

After the synoptic table we illustrate a brief guide of how to install and use the selected kit to allow any comparison to other existing software.

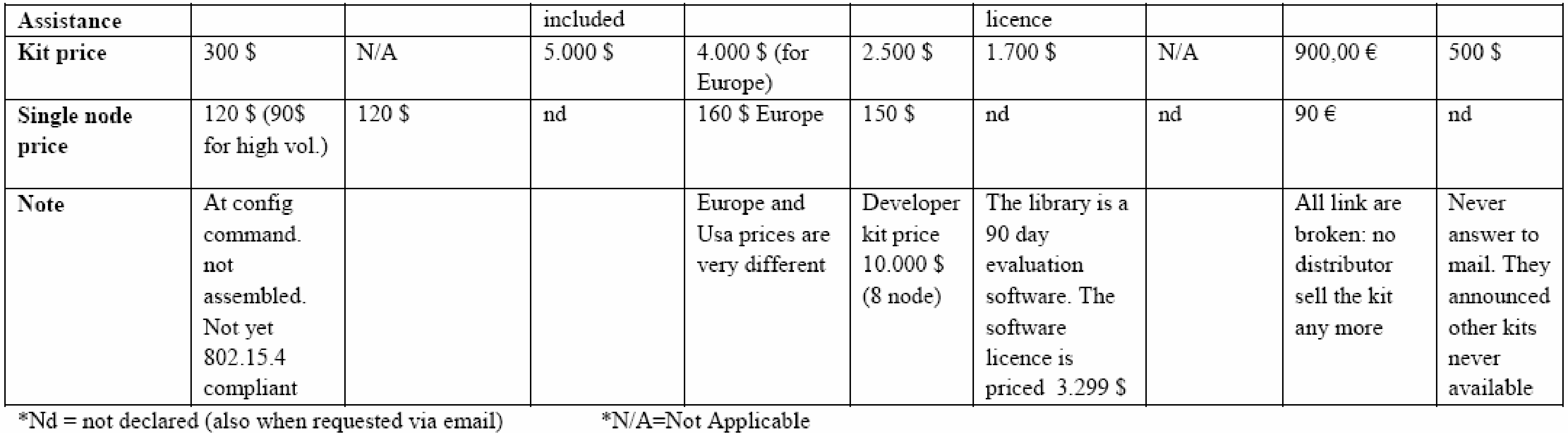


Manufacturer	Aerocomm	Art of Technology	Chipcon	Crossbow	Ember	Freescale	Imote iv	Infineon	Jennic
Node name	ZB2430-N	Btnode 3		micaz	EM250	1321x-NCB	telos A	eyes tda5250	JN5139
Kit name	AeroComm's Design Kits	No kit	CC2420ZDK ZigBee(TM) Development Kit	WSN OEM Design Kit (WSN-OEM2400CA)	InSight Jumpstart kit	1321xEVK: MC1321x Evaluation Kit (HW only)	N/A	EyesIFX v2.1 Developer kit	JN5139 ZigBee Evaluation Kit
Number of node in the kit	2	N/A	5	5+ 1 Gateway	3	3 (plus 4 sensor board)	N/A	5	1 FFD +4 RFD
Coordinator node is different	No	Yes	Yes	Yes	Yes	No	No	No	Yes
Microcontroller	ZB2430	Atmel Atmega 128L	Atmel	Atmel Atmega 128L (Intel PXA271 Processor 416Mhz Gateway)	AP2b 16-bit	Freescale HCS08	Texas Instruments MSP430	Texas Instruments MSP430F	32-bit RISC CPU
Clock	4 Mhz	7.37 MHz	8 MHz	7.37 MHz	12 Mhz	8 Mhz	8 MHz	8 MHz	16 Mhz
RAM (KB)	4	64 + 180	4	4	5	4	2	10	96
ROM (KB)	128	128	128	128	128	60	60	48	192
Storage (KB)	4	4	4	512	nd	1	256	512	nd
Radio	ZB2430 250 kbps RF data stream 2400-2483.5 MHz 2.402 - 2.478 GHz FHSS FSK	Chipcon CC1000 315/433/868/916 MHz 38.4 Kbauds	nd	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	ZigBee 802.15.4 2,4 Ghz	13202RFC 2.4GHz 802.15.4 ZigBee	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	868 MHz (64 kbps ASK/FSK Infineon Wireless Transceiver TDA5250)	ZigBee 802.15.4

Table B.1a - The Development Kit s

Max Range	135 m	150–300 m	75–100 m	150–300 m	75–100 m	75–100 m	75–100 m	nd	80–200 m
Power	nd	2x AA batteries	4 x 1,5 AA	3x AAA	4x AA	nd	2x AA batteries	Lithium 3V batteries (CR2025)	2 x AAA
Node Power consumption	Sleep mode 25/45 mA Tx/Rx 123/100 mA	nd	nd	390 µA In Deep Sleep, 66 mA Active Mode, max 500mA Tx/Rx	Deep sleep 1.0µA (mcu)	nd	Not declared	TX: typ. 10mA RX: typ. 8 mA @ 3V Power down max. 100nA	Tx current 39mA Deep sleep <0.4µA
PC connector	Serial up to 115.2 kbps	PC-connected programming board	PC-connected programming board	PC-connected programming board	nd	nd	USB	USB	nd
OS	N/A	Nut/OS	nd	TinyOS	TinyOS	nd	TinyOS	nd	nd
AC Power Adapters	2	0	0	0		3	0	0	0
On Board sensors	nd	nd	nd	Separate Sensor Boards	nd	nd	nd	Temp (LM61) e Light (NSL19M51) e RSSI	Temp, light, RH (model not specified)
Software included	Software Utilities	nd	Z-Stack - ZigBee Protocol Stack	Moteworks standard edition software license	InSight Desktop Developer Edition (1 Seat), xIDE Compiler	90-day evaluation Beestack™ ZigBee stack. CodeWarrior™ Development Studio HCS08	nd	nd	nd
Devel.	60 day	nd	6 month	nd	nd	Only with Sw	nd	nd	nd

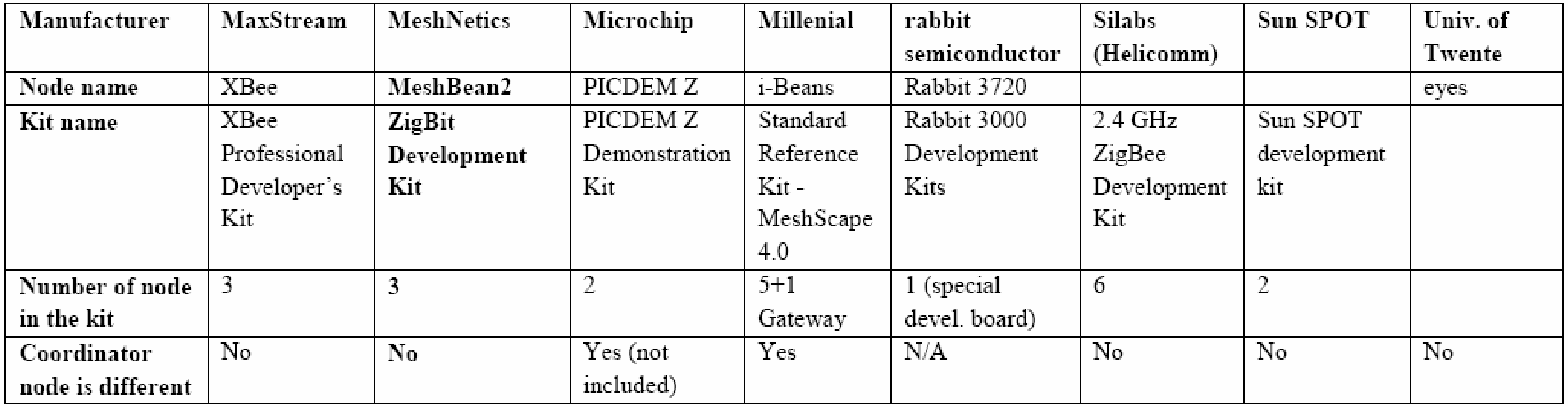
Table B.1b - The Development Kit s



Assistance			included			licence			
Kit price	300 $	N/A	5.000 $	4.000 $ (for Europe)	2.500 $	1.700 $	N/A	900,00 €	500 $
Single node price	120 $ (90$ for high vol.)	120 $	nd	160 $ Europe	150 $	nd	nd	90 €	nd
Note	At config command. not assembled. Not yet 802.15.4 compliant			Europe and Usa prices are very different	Developer kit price 10.000 $ (8 node)	The library is a 90 day evaluation software. The software licence is priced 3.299 $		All link are broken: no distributor sell the kit any more	Never answer to mail. They announced other kits never available

*Nd = not declared (also when requested via email) *N/A=Not Applicable

Table B.1c - The Development Kit s

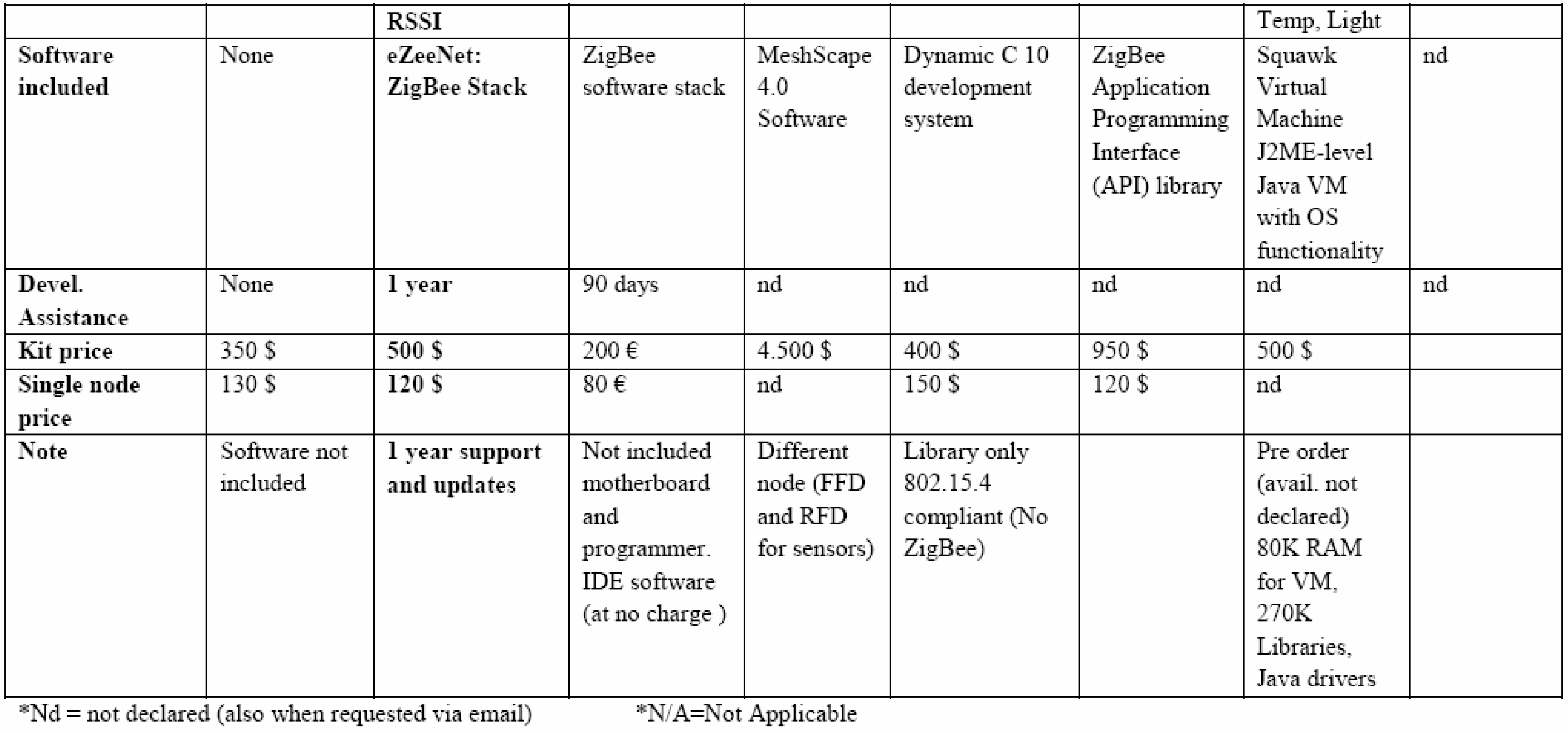


Manufacturer	**MaxStream**	**MeshNetics**	**Microchip**	**Millenial**	**rabbit semiconductor**	**Silabs (Helicomm)**	**Sun SPOT**	**Univ. of Twente**
Node name	XBee	**MeshBean2**	PICDEM Z	i-Beans	Rabbit 3720			eyes
Kit name	XBee Professional Developer's Kit	**ZigBit Development Kit**	PICDEM Z Demonstration Kit	Standard Reference Kit - MeshScape 4.0	Rabbit 3000 Development Kits	2.4 GHz ZigBee Development Kit	Sun SPOT development kit	
Number of node in the kit	3	**3**	2	5+1 Gateway	1 (special devel. board)	6	2	
Coordinator node is different	No	**No**	Yes (not included)	Yes	N/A	No	No	No

Table B.2a - The Development Kit s

Microcontroller	ndn	**ATmega 1281V**	PIC18LF4620	Not declared	Rabbit 3720	C8051F121	32 bit ARM920T	Texas Instruments MSP430
Clock	nd	**4-8Mhz**	4 MHz	N/A	22,1 Mhz	24.5 MHz	180 MHz	5MHz
RAM (KB)	nd	**8**	4	N/A	512	8	256	2
ROM (KB)	nd	**128**	64	N/A	256	128	2048	60
Storage (KB)	nd	**4**	1	N/A	1024			4
Radio	XBee ZigBee™ 802.15.4	**AT86RF230-ZU - 2.4GHz 802.15.4/ZigBee**	MRF24J40 RF 2.4GHz 802.15.4 ZigBee or MiWi	IEEE 802.15.4	MaxStream XBee RF 802.15.4	ZigBee™ and IEEE 802.15.4 From Helicomm	Chipcon CC2420 802.15.4	RFM TR1001868 MHz 57.6 Kbps
Max Range	90 m	**100-150 m**	nd	nd	90 m	nd	nd	75–100 m
Power	9 V battery clip on external board	**2x AA batteries**	9V battery	CR2032	3x AAA batteries	9V battery	2xAA	2 AA batteries
Node Power consumption	215 mA <10 µA in sleep mode	**200 mA <20 µA in sleep mode**	nd	Not declared	150 mA transmitting, 80 mA normal operation , <20 µA in sleep mode		25-90mA	
PC connector	Serial RS 232	**USB / serial**	nd	RS-232 and RS-485	Ethernet	USB		Serial Port
OS	None	**TinyOS**	nd	nd	nd	nd	nd	PEEROS
AC Power Adapters	0	**3**	nd	Not declared	nd	nd	nd	nd
On Board sensors	None	**SL2550 Light, LM73 Temp,**	TempTC77	Not declared	None	nd	2G 3-axis accelerometer	nd

Table B.2b - The Development Kit s



		RSSI					Temp, Light	
Software included	None	**eZeeNet: ZigBee Stack**	ZigBee software stack	MeshScape 4.0 Software	Dynamic C 10 development system	ZigBee Application Programming Interface (API) library	Squawk Virtual Machine J2ME-level Java VM with OS functionality	nd
Devel. Assistance	None	**1 year**	90 days	nd	nd	nd	nd	nd
Kit price	350 $	**500 $**	200 €	4.500 $	400 $	950 $	500 $	
Single node price	130 $	**120 $**	80 €	nd	150 $	120 $	nd	
Note	Software not included	**1 year support and updates**	Not included motherboard and programmer. IDE software (at no charge)	Different node (FFD and RFD for sensors)	Library only 802.15.4 compliant (No ZigBee)		Pre order (avail. not declared) 80K RAM for VM, 270K Libraries, Java drivers	

*Nd = not declared (also when requested via email) *N/A=Not Applicable

Table 4.2c - The Development Kit s

PC Software Installation

The developing system require several component to be downloaded directly from the manufacturer an example maybe the USB driver, fitting different Windows versions, and available from the Silicon Laboratories (Silabs) website.

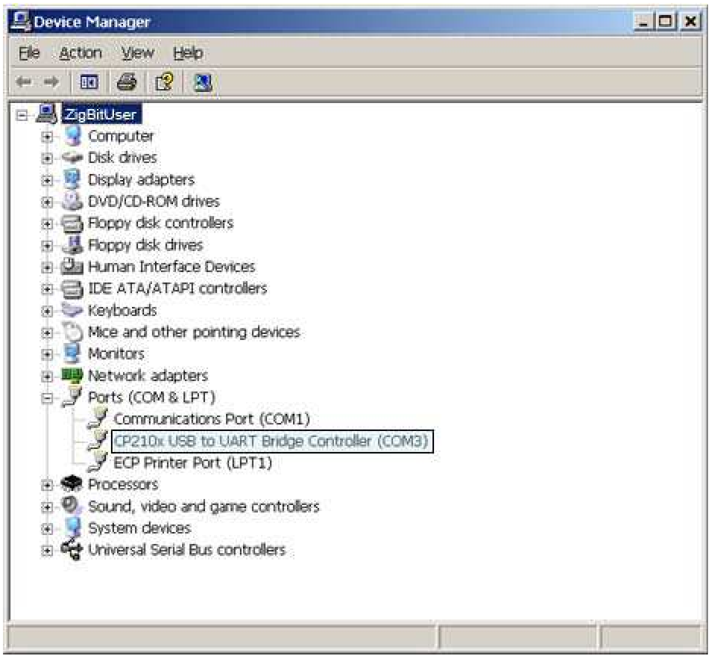


Figure B.1 - COM port drivers in the Windows Device Manager window

After installation of the Virtual Com Port (VCP) driver kit the MeshBean2 board can be connected to the USB port. Windows should detect the new hardware, and driver installation wizard will appear, performing the windows' standard procedure.

When the process is completed, the new COM port is present in the device list and can be used freely (see fig. B.1).

Programming the Boards

The MeshBean boards come with a test software installed, so at node start-up, if we press and hold the SW1 onboard button (see Figure 5.2 for at least 1 second, the LED1 will get flashing 3 times. Next, LED1, LED2 and LED3 will start blinking for 2 sec. This means the board is fully functional and with the Serial boot loader installed.

All the boards can be programmed in two ways: either you can use Serial Boot loader utility or you can do it under AVR Studio, using JTAG emulator like JTAGICE mkII from Atmel, employed in our development.

The choice between the boot loader and the jtag programmer must be done wisely since each one of MeshBean2 boards come with the bootstrap downloaded into the MCU, which is needed to run Serial Boot loader.

If JTAG has been used, it will make impossible using Serial Boot loader, unless bootstrap is reloaded to the board.

Using Serial Boot loader

To program a board using Serial Boot loader do the following steps:

1. Connect the board to the PC via USB or RS-232 port
2. Run Serial Boot loader specifying the image file, COM port and the optional keys in command line (see table 5.3).
3. Press reset button on the board.
4. Release reset button on the board.

This procedure must be preceded by a complete power off if the node has been configured as end-device and it is currently controlled by the running application.

The Serial Boot loader indicates the operation progress and once loading is finished successfully, the board will restart automatically. If, for any reason, the loading procedure fails, the Serial Boot loader will indicate the reason.

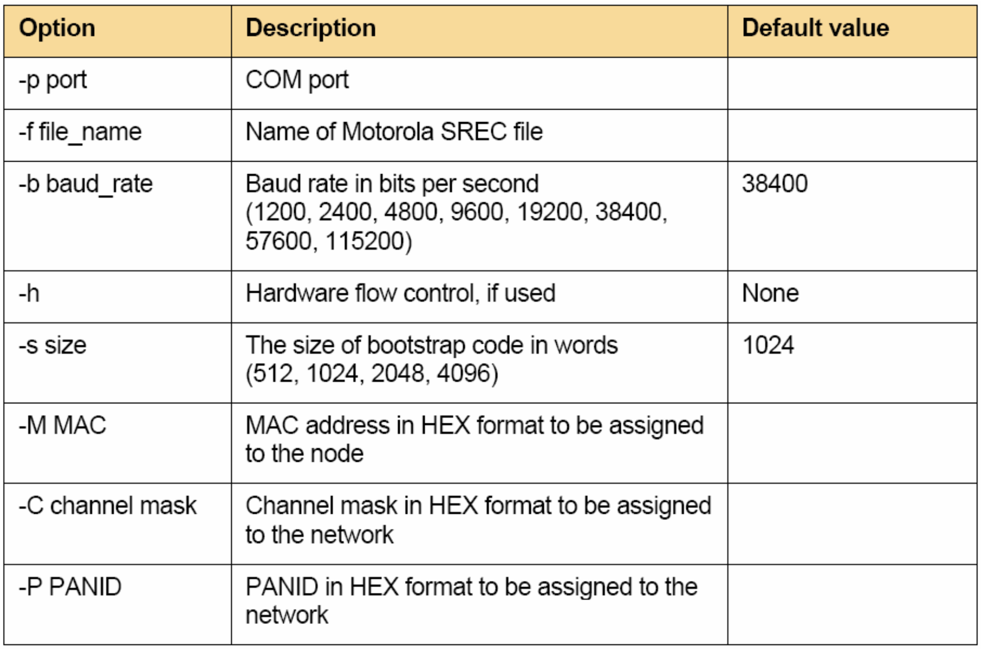
In rare cases the booting process can fail due to the communication errors between the board and the PC and must be repeated.

In the following example of how to use the Serial Boot loader, from a command window:

```
bootloader –f wsnapp.srec –p COM5 –M 1 –C 100000
–P 5320
```

In this example we are programming the node via the com port number 5 (the one where the node is connected to) writing in it the new program program file (wsnapp.srec) and assigning a new MAC address equal to 1 (-M 1), a channel mask allow in only one channel (-C option) and a network id of 5320 (-p option).

Thus, as our example shows, we can define, via serial commands, the boards MAC address, that must be unique for each node to get interconnected in WSN network and many other parameters (shown in table B.3).



Option	Description	Default value
-p port	COM port	
-f file_name	Name of Motorola SREC file	
-b baud_rate	Baud rate in bits per second (1200, 2400, 4800, 9600, 19200, 38400, 57600, 115200)	38400
-h	Hardware flow control, if used	None
-s size	The size of bootstrap code in words (512, 1024, 2048, 4096)	1024
-M MAC	MAC address in HEX format to be assigned to the node	
-C channel mask	Channel mask in HEX format to be assigned to the network	
-P PANID	PANID in HEX format to be assigned to the network	

Table B.3 - Bootloader Options

In general if the MAC address is not defined by hardware, the node ID derived from MAC should be programmed avoiding any duplication of MAC address and of the short address often created using the MAC address itself.

Programming a MeshBean2 board with MAC address can be performed in two alternative ways: MAC address can be downloaded to a board by means of Serial Bootloader running with the key specified within command line or MAC address can be programmed using SerialNet AT-commands.

Using JTAG

The board can be programmed also using the JTAG connector. The JTAG programmer/debugger must be linked together with the MeshBean on-board JTAG connector (see Figure 5.2 for more detail and table B.4 for JTAG connector pin out).

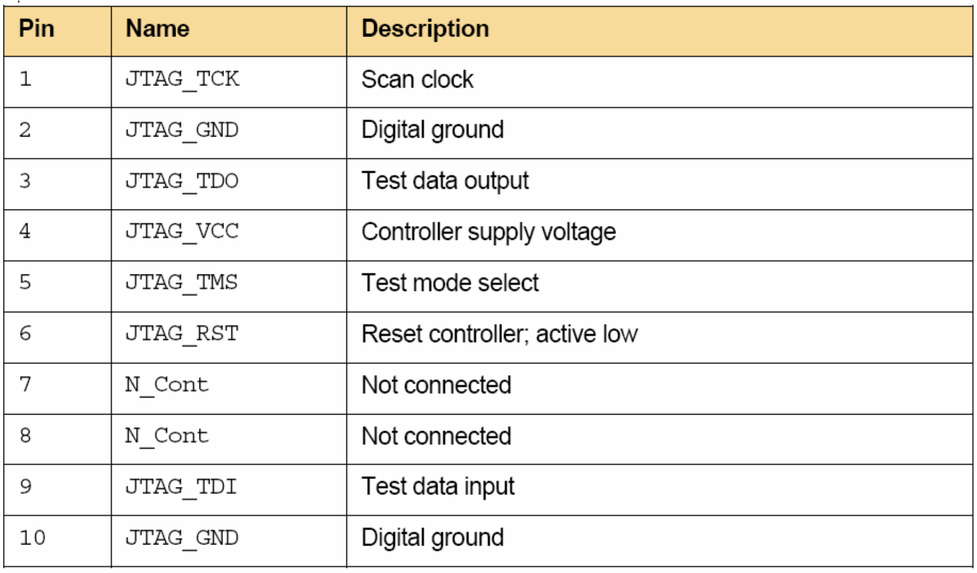
While using the JTAG interface, the Fuses state must be checked carefully because an error in setting their value may cause the impossibility to reprogram the MCU again.

Some of the Fuses option must be always in a ON status like in the next screen:

```
Brown-out detection disabled; [BODLEVEL=111]

JTAG Interface Enabled; [JTAGEN=0]

Serial program downloading (SPI) enabled; [SPIEN=0]

Boot Flash section size=1024 words Boot start
address=$FE00;[BOOTSZ=10]

Divide clock by 8 internally; [CKDIV8=0]

Int. RC Osc.; Start-up time: 6 CK + 65 ms;
[CKSEL=0010 SUT=01]
```

At the bottom of Fuses Tab the following hex value string must appears: **0xFF, 0x9D, 0x62**, otherwise the node can’t be reprogrammed.
Additionally if we want to use the Serial Bootloader we need in ON status also the next values:

```
Boot Reset vector Enabled (default address=$0000);
[BOOTRST=0]
```

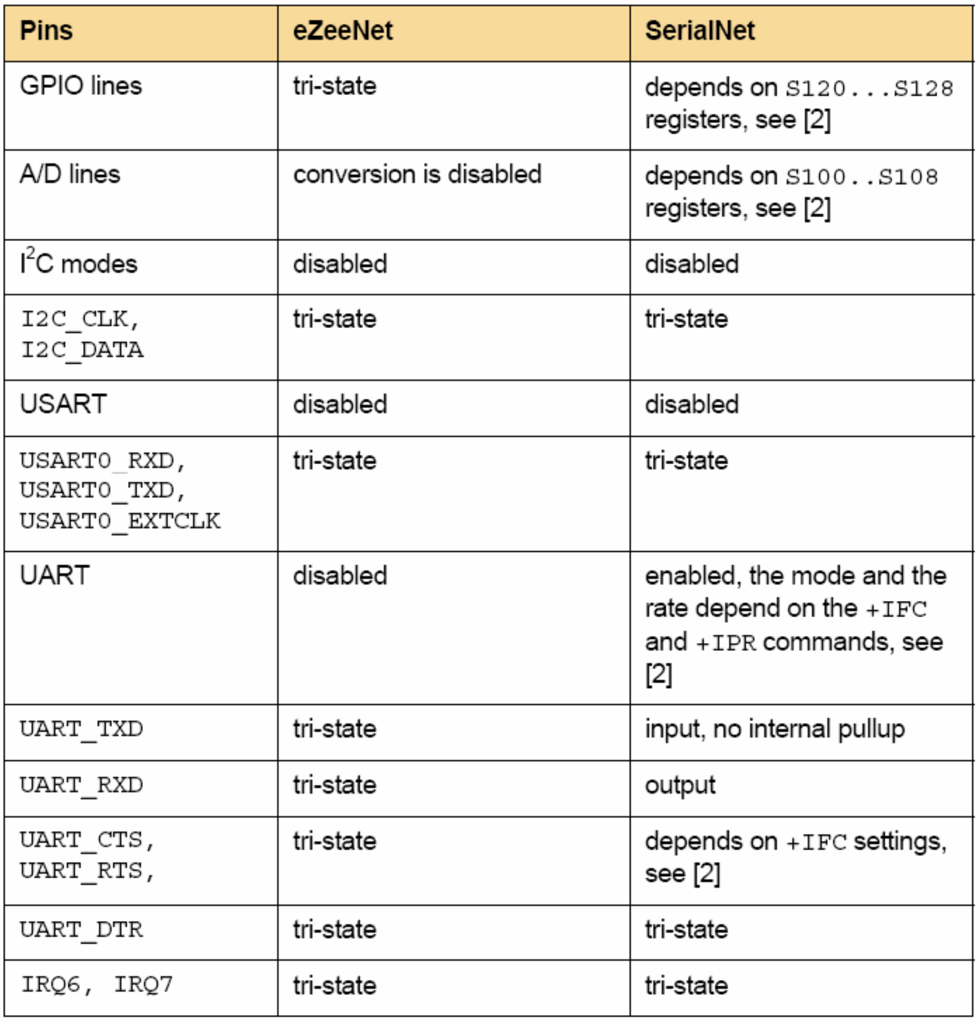


Pin	Name	Description
1	JTAG_TCK	Scan clock
2	JTAG_GND	Digital ground
3	JTAG_TDO	Test data output
4	JTAG_VCC	Controller supply voltage
5	JTAG_TMS	Test mode select
6	JTAG_RST	Reset controller; active low
7	N_Cont	Not connected
8	N_Cont	Not connected
9	JTAG_TDI	Test data input
10	JTAG_GND	Digital ground

Table B.4.- JTAG connector pin out

And in this last case the following hex value string appears at the bottom of Fuses Tab: **0xFF, 0x9C, 0x62**. By default, each MeshBean node (MCU) comes programmed with the fuse bit latter option above enabled.

JTAG can also be used to restore the device's ability to respond to Serial Bootloader commands. Serial Bootloader code can be reprogrammed with JTAG by selecting bootloader.hex image from the ZDK cd that comes with the Development kit and transferring the image to the device.



Pins	eZeeNet	SerialNet
GPIO lines	tri-state	depends on S120...S128 registers, see [2]
A/D lines	conversion is disabled	depends on S100..S108 registers, see [2]
I^{2}C modes	disabled	disabled
I2C_CLK, I2C_DATA	tri-state	tri-state
USART	disabled	disabled
USART0_RXD, USART0_TXD, USART0_EXTCLK	tri-state	tri-state
UART	disabled	enabled, the mode and the rate depend on the +IFC and +IPR commands, see [2]
UART_TXD	tri-state	input, no internal pullup
UART_RXD	tri-state	output
UART_CTS, UART_RTS,	tri-state	depends on +IFC settings, see [2]
UART_DTR	tri-state	tri-state
IRQ6, IRQ7	tri-state	tri-state

*[2] = eZeeNet™ Software 1.4. SerialNet™ Reference Manual. AT-Command Set. MeshNetics Doc. P-EZN-452~01

Table B.5 - HAL resources state at startup

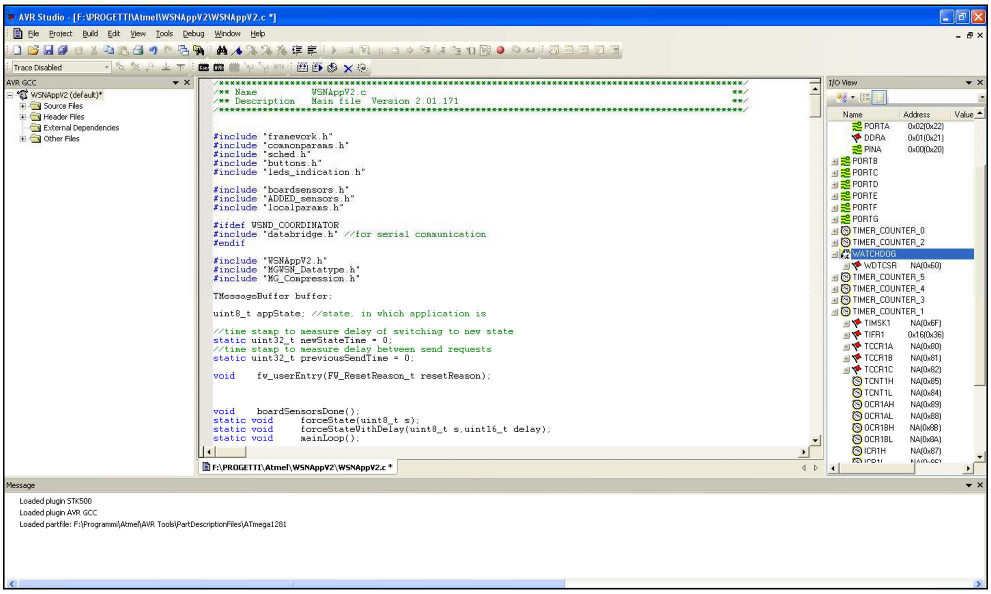
Using AVR Programming Tools

The Atmel's AVR Studio IDE shown in Figure 4.6 is recommended, not only because it is free of charge and downloadable from the Atmel (the

MCU’s manufacturer) site, but also to develop custom applications based on eZeeNet API.

This multiplatform Integrated Development Environment provides support for editing the source code, compilation, linking object modules with libraries, debugging, making executable file automatically, and, if you have a compatible with the JTAG programmer it allows the application writing directly in the MCU flash memory.

AVR Studio can be integrated with WinAVR: a suite of very useful software development tools for the Atmel AVR series of RISC microprocessors hosted on the Windows platform.


AVR Studio - [F:\PROGETTI\Atmel\WSNAppV2\WSNAppV2.c *]
File Project Build Edit View Tools Debug Window Help
Trace Disabled
AVR GCC
WSNAppV2 (default)*
Source Files
Header Files
External Dependencies
Other Files
I/O View
F:\PROGETTI\Atmel\WSNAppV2\WSNAppV2.c *
Message

```
/*****************************************************************************************/
/** Name           WSNAppV2.c                                                          **/
/** Description    Main file  Version 2.01.171                                         **/
/*****************************************************************************************/


#include "framework.h"
#include "commonparams.h"
#include "sched.h"
#include "buttons.h"
#include "leds_indication.h"

#include "boardsensors.h"
#include "ADDED_sensors.h"
#include "localparams.h"

#ifdef WSND_COORDINATOR
#include "databridge.h" //for serial communication
#endif

#include "WSNAppV2.h"
#include "MGWSN_Datatype.h"
#include "MG_Compression.h"

TMessageBuffer buffer;

uint8_t appState; //state, in which application is

//time stamp to measure delay of switching to new state
static uint32_t newStateTime = 0;
//time stamp to measure delay between send requests
static uint32_t previousSendTime = 0;

void    fw_userEntry(FW_ResetReason_t resetReason);



void    boardSensorsDone();
static void     forceState(uint8_t s);
static void     forceStateWithDelay(uint8_t s,uint16_t delay);
static void     mainLoop();
```

Name	Address	Value
PORTA	0x02(0x22)	
DDRA	0x01(0x21)	
PINA	0x00(0x20)	
PORTB		
PORTC		
PORTD		
PORTE		
PORTF		
PORTG		
TIMER_COUNTER_0		
TIMER_COUNTER_2		
WATCHDOG		
WDTCSR	NA(0x60)	
TIMER_COUNTER_5		
TIMER_COUNTER_4		
TIMER_COUNTER_3		
TIMER_COUNTER_1		
TIMSK1	NA(0x6F)	
TIFR1	0x16(0x36)	
TCCR1A	NA(0x80)	
TCCR1B	NA(0x81)	
TCCR1C	NA(0x82)	
TCNT1H	NA(0x85)	
TCNT1L	NA(0x84)	
OCR1AH	NA(0x89)	
OCR1AL	NA(0x88)	
OCR1BH	NA(0x8B)	
OCR1BL	NA(0x8A)	
ICR1H	NA(0x87)	

```
Loaded plugin STK500
Loaded plugin AVR GCC
Loaded partfile: F:\Programmi\Atmel\AVR Tools\PartDescriptionFiles\ATmega1281
```

Figure B.2 – The AVR Studio 4 IDE at work

WinAVR contains a set of utilities including AVR GCC compiler, linker, automatic Makefile generator, system libraries.

Installing the AVR GCC plug-in lets those tools working automatically in AVR Studio. The GCC plug-in is configured to work only on Windows platform and configured to compile C or C++ codes (the Linux version at this time is not supported).

There are some equivalent IDE and JTAG programmer support, such as AVaRICE, also for the Linux platform and the GCC compiler has added the support for the AVR series of microcontrollers.

The easiest way to configure an AVR project is to use a Makefile which specifies compilation and linking flags. Makefile also specifies

corresponding directories in order to include header files and to link the system object libraries.
An example of a minimum application is provided in Appendix C

JTAG emulator

Programming with JTAG gives more flexibility in managing the loading process than the Serial boot loader but requires special hardware.
For Windows environment we used, as recommended, the AVR Studio 4.12 (actually is available the version 4.18) while Linux platform AVaRICE 2.40 was available. In both cases, the JTAG emulator JTAGICE mkII (see fig. B.3) from Atmel was the programmer chosen because of its debugging capabilities. Other programming devices can be utilized as well, but, although are less expensive, they usually don’t have any debugging feature available and sometimes they require special plugin to be used by the AVR IDE.

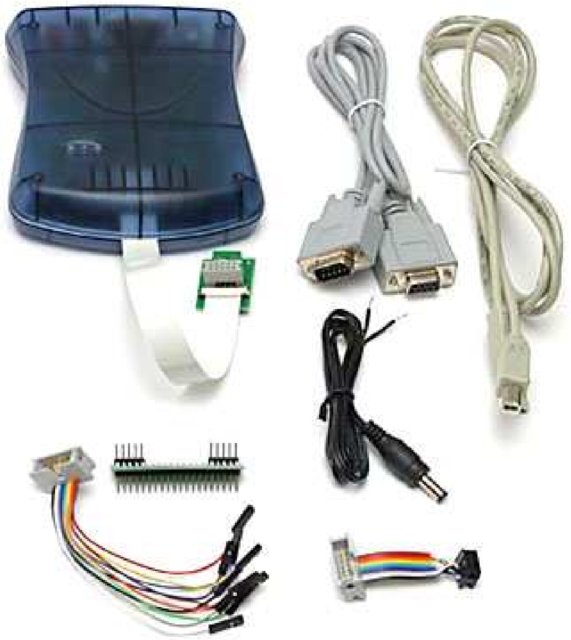
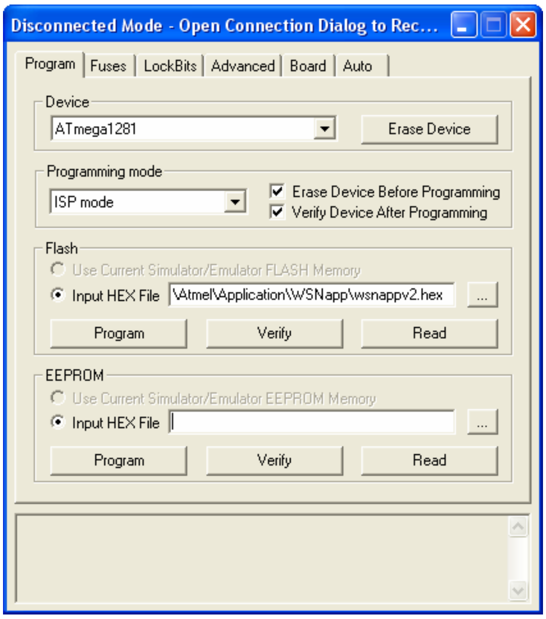


Figure B.3- JTAGICE mkII programmer

The Atmega1281 MCU HEX files for Serial Boot loader, provided on the kit cd, contain both flash memory and EEPROM images (MOTOROLA version).

AVR Studio does not support downloads of such combined files into the MCU. Instead, it requires separate images for flash memory and EEPROM, and it recognizes files in the Intel HEX format only.

This is the reason why we ask to the kit manufacturer to deliver also two separate image files in the Intel HEX format that are downloadable by AVR Studio or other JTAG tools.



Device: ATmega1281

Programming mode: ISP mode

☑ Erase Device Before Programming

☑ Verify Device After Programming

Flash

○ Use Current Simulator/Emulator FLASH Memory

● Input HEX File \Atmel\Application\WSNapp\wsnappv2.hex

EEPROM

○ Use Current Simulator/Emulator EEPROM Memory

● Input HEX File

Figure B.4 - AVR Studio dialog box for JTAG firmware downloading

C.

Data compression

A definition of data compression

Let us formalize a definition of data compression.

Assuming that $x = x_1x_2 \dots x_n$ is a sequence. The sequence length, denoted by n, is the number of elements in x, and x_i denotes the ith element of x.

We also define the *reverse sequence*, x−1, as $x_nx_{n-1} \dots x_1$. Given a sequence x let us assume that x = uvw for some, possibly empty, subsequences u, v, w. Then u is called a *prefix* of x, v a *component* of x, and w a *suffix* of x. Each element of the sequence, x_i, belongs to a finite ordered set $A = \{a_0, a_1, \dots, a_{k-1}\}$ that is called an *alphabet*.

The number of elements in A is the size of the alphabet and is denoted by k. The elements of the alphabet are called *symbols* or *characters*.

A special term for a non-empty component of x consisting of identical symbols is called a *run*. To simplify the notation we denote the component $x_ix_{i+1} \dots x_j$ simply $x_{i..j}$.

Except the first one, all characters x_i in a sequence x are preceded by a nonempty prefix $x_{(i-d)..(i-1)}$. We name this prefix a *context of order d* of the x_i. If the order of the context is unspecified we arrive at the longest possible context $x_{1..(i-1)}$ that we simply call it a *context of x_i*.

Modelling and coding

The modern compression splits the compression algorithm into two different stages: modelling and coding. The reason is quite simple: first of all, we must recognise the sequence, then look for regularities and similarities.

This is the task of modelling. The modelling method, indeed, is specialised for the type of data we compress. It is obvious that in video data we will be searching for different similarities than in text data. Applying the proper modelling method is important for the final results. In particular, we cannot reduce the sequence length at all if we do not know what is redundant in it.

The second stage, coding, is based on the knowledge obtained in the modelling stage, and removes the redundant data.

The coding methods are usually very similar because the modelling process is the stage where the adaptation to the data is made.

Modelling

The modeling stage analyze the sequence to compress, building a model to estimate the probability distribution of symbols' occurrences and allowing, in this way, the prediction of future symbols in the sequence

The simplest way of modeling is to use a pre-calculated table of probabilities of symbol occurrences [Deo03]. The better is our symbol occurrences knowledge the better we can predict the future characters.

We can use pre-calculated tables only if we know exactly what we compress. If we know that the input sequence is an Italian text, we can use typical frequencies of character occurrences.

Otherwise, if we do not know the language of the text, and we use, for instance , the pre-calculated table for the Italian language to a German text, we will achieve much worse results, because the difference between the input frequencies and the pre-calculated ones is usually big.

Furthermore, the probability of symbol occurrences differs from text to text depending from various parameters such as the authors.

So a better way to build the model is not to assume too much about the sequence and realize the model from the encoded part of the sequence. During the decompression process, the decoder can build its own model in the same way.

This compression approach is called adaptive, because the model is built only from past symbols and adapts itself to the contents of the sequence. We could not use the future symbols because they are unknown to the decompressor.

Other methods, usually static, build the model from the whole sequence and then use it. The decompressor has no knowledge of the input sequence, and the model has to be stored in the output sequence, too. The static approach is usually avoided because requires much more computation while is can be proved that the adaptive way is equivalent.

Entropy coding

The second stage of the compression method is the entropy coding. The entropy coding is based on a probability distribution of occurrences of the symbols, which is prepared by the modeling stage, and then compress these characters.

When we know the probability of occurrences of every symbol from the alphabet, but we do not know the current character, the best solution is, probably, to assign to each character a code of length [HiL92].

$$\textbf{(C.1)} \quad \log_2 \frac{1}{p_i} = -\log_2 p_i$$

where p_i is the probability of occurrence of symbol a_i If we do so, the expected code length of the current symbol is

$$\textbf{(C.2)} \quad E = -\sum_{i=0}^{k-1} p_i \cdot \log_2 p_i$$

The difference between these codes and the ones used for representing the symbols in the initial sequence has a simple reason: the codes have different length, while such codes as ASCII or Unicode store all symbols using the identical number of bits.

The expected code length of the current symbol is not greater than the code length of this symbol. Replacing all characters from the input sequence with codes of smaller length causes a reduction of the total length and this is what gives us compression. Must be noted that if the modeling stage produces wrong estimated probabilities, the sequence can expand during the compression.

For example let us assume that we have to compress the German letter ã for which the expected probability is 0 (in Italian). Using the rule of the best code length (C.1) the coder would generate an infinite length code.

Huffman coding

The formulas C.1 means that we usually should assign codes of non integer length to most symbols from the input sequence.

It is possible: in fact and this coding procedure was introduced by Huffman [Huf52] in 1952.

Assuming that we have a table symbol occurrences frequencies in the encoded part of the sequence, we start building a tree by creating the leaves:

- Create one leaf for each symbol from the alphabet.
- Create a common parent for the two nodes without parents and with the smallest frequency.
- Assign to the new node a frequency being a sum of the frequencies of its sons.
- Repeat the last passage until there is only one node without a parent.

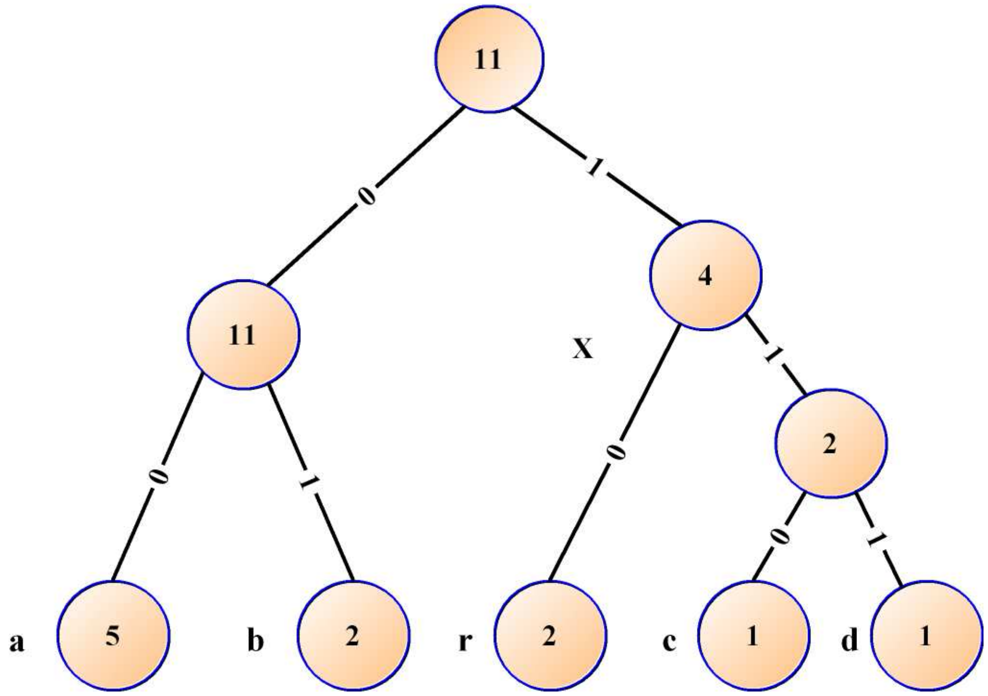


Figure C.1– Huffman tree for the sequence abracadabra

This node will be the root of the tree. After the tree building process we create the code for a given symbol, starting from the root and moving towards the leaf corresponding to the symbol, starting with an empty code, and whenever we go to a left son, we append 0 to it, whenever we go to a right son, we append 1. When we arrive to the leaf, the code for the symbol is ready.

This procedure is repeated for all symbols. Figure C.1 illustrates an example of the Huffman tree and the codes for symbols after processing a sequence *abracadabra* (a very classic word used in compression examples).

While building the tree, if there are two nodes with the same frequency we can choose any of them thus means that there are more than one possible Huffman tree for our data.

Although the Huffman coding is simple, rebuilding the tree after processing each character is quite complicated. It was shown by Gallager that its maximum inefficiency, (the maximum difference between the expected code length and the optimum) is bounded by:

$$\textbf{(C.3)} \quad p_m + \log_2 \frac{2\log_2 e}{e} \approx p_m + 0{,}086$$

where p_m is the probability of occurrence of the most frequent symbol.

Usually the loss is smaller of the estimation and due to the simplicity and effectiveness of the compression, this algorithm is often used when compression speed is important.

The Huffman coding was deeply studied during the years. Some examples were provided by Knuth [Kun85] and Cormack [CoH84], where they show methods of storing and maintaining the Huffman tree.

D.

Acronyms

AES	Advanced Encryption Standard
AIB	APS Information Base (also APS IB)
AODV	Ad-hoc On-demand Distance Vector (routing)
APL	Application (Layer)
APS	APplication Support (layer or sub-layer)
APS IB	APS Information Base (also AIB).
APSDE	APS Data Entity
APSDE-SAP	APS Data Entity Service Access Point
APSME	APS Management Entity
ARP	Address Resolution Protocol
ASDU	APS Sublayer Data Unit
BLE	Battery Life Extention
CAP	Contention Access Period
CCA	Clear Channel Assessments
CFP	Contention Free Period
CID	Cluster IDentity
CMOS	Complementary Metal Oxide Semiconductor
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DLL	Data Link Layer
DOS	denial-of-service (attack)
DSSS	Direct-sequence spread-spectrum

EEG	Electroencephalography
EMP	Electromagnetic pulse
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FFD	Full Function Device
FHSS	Frequency-hopping spread spectrum
FRAM	Ferroelectric Non-volatile RAM
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
GRAd	Gradient routing
GTS	Guaranteed Time Slots
HAL	Hardware Abstraction Layer
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IETF	Internet Engineering Task Force
ISR	Interrupt Service Routine
LLC	logical link control (layer)
LQI	Link Quality Indication
MAC	Medium Access Control (layer)
MEMS	Microelectromechanical Systems
MIC	Message Integrity Code
MISO	Master Out Slave In (data line)
MLME	MAC Layer Management Entity
MLME-SAP	MAC Layer Management Entity Service Access Point
MOSI	Master In Slave Out (data line)
NIB	Network Layer Information Base
NIDS	Network Intrusion Detection System
NLME	Network Layer Management Entity
NLME-SAP	Network Layer Management Entity Service Access Point
NWK	network (layer)

ODV	On-demand Distance Vector
OSI	Open Systems Interconnection
PAN	Personal Area Network
PD	PHY Data
PD-SAP	PHY Data Service Access Point
PHI	Physical (layer)
QOS	Quality of Service
RDT	Route Discovery Table
RFD	Reduced Function Device
RIP	Routing Information Protocol
RKE	Remote Keyless Entry
RREP	Route REPly
RREQ	Route REQuest
RSSI	Received Signal Strength Indication
RT	Route Table
SCL	Serial Clock (line)
SS	Slave Select (also called !SS)
SSP	Security Services Provider
VCP	Virtual Com Port (driver USB-to-Com)
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
ZDO	ZigBee device object
ZDP	ZigBee device profile

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