Technic University of Madrid

Higher Technical School of
Telecommunications Engineering

FINAL THESIS REPORT

M.S. Degree in Telecommunication Engineering

Development of a multiple RF interfaced platform for Cognitive Wireless Sensor Networks

Agustín Tena García

September 2013

Documento formatted with TEXIS v.1.0+.

This document is prepared for duplex printing.

Final Thesis Report

Title:	Development of a multiple RF interfaced platform for Cognitive Wireless Sensor Networks
Author:	Agustín Tena García
Advisor:	Elena Romero Perales
Inspector:	Alvaro Araujo Pinto
Departament:	Electronic Engineering Department

Thesis Committee

President:	D. Álvaro de Guzman Fernández González
Member:	D. Alvaro Araujo Pinto
Secretary:	D. Pedro José Malagón Marzo
Assistant:	D. Miguel Ángel Sánchez García

SCORE:

It is certified that Agustín Tena García has successfully accomplished his Final Thesis Report, thus obtaining the M.S. Degree in Telemmunications Engineering at Higher Technical School of Telecommunications Engineering, Technical University of Madrid, Spain.

Madrid, a de de

Development of a multiple RF interfaced platform for Cognitive Wireless Sensor Networks

AUTHOR: Agustín Tena García

ADVISOR: Elena Romero Perales

INSPECTOR: Alvaro Araujo Pinto

Electronic Engineering Department
Higher Technical School of Telecommunications Engineering
Technic University of Madrid

September 2013

A mis abuelos

Acknowledgements

Abstract

Nowadays, Wireless Sensor Networks are subject to development constraints and difficulties such as the increasing RF spectrum saturation. This brings hindrances to Wireless Ad-hoc Sensor Networks deployment, especially for critical and sensitive applications.

Cognitive Networks (CN), leaning on a cooperative communication model, represent a new paradigm aimed at improving wireless communications. Cognitive Wireless Sensor Networks (CWSNs) compound cognitive properties into common WSNs, developing new strategies to mitigate difficulties arising from the constraints these networks face regarding energy and resources.

It is important to investigate cognitive models to explore their benefit over our WAHSNs. However, few platforms allow their study due to their early research stage, and they still show scarce or specific features. Investigations take place mainly over simulators, which provide partial and incomplete results.

This paper presents a versatile platform that brings together cognitive properties into WSNs. It combines hardware and software modules as an entire instrument to investigate CWSNs. The hardware fits WSN requirements in terms of size, cost and energy. It allows communication over three different RF bands, ~~becoming~~ the only cognitive platform for WSNs with this capability. ~~Besides~~ its modular and scalable design is widely adaptable to almost any WAHSN application.

KEY WORDS: *cognitive, wireless sensor networks, platform.*

Index

List of Figures

List of Tables

Chapter 1

Introduction

Something in the air

Thomas & Guy-Manuel, Daft Punk

In this chapter, a global description of the project is shown. This global description covers an introduction to the context, the need of this project and a brief description of it. It defines goals and the project organization in time. Besides, ~~it is described the structure of this dissertation~~.

1.1. Background

A WSN (*Wireless Sensor Network*) consists of a number of sensors spread across a geographical area. Each sensor has wireless communication capability and some level of intelligence for signal processing and networking of the data. WSNs have recently emerged as a premier research topic since they provide a decentralized technological solution to address applications related to security and surveillance, industrial control, infrastructure maintenance, automatic environmental monitoring, domotics, localization and tracking or health. They ~~have~~ great long-term economic potential and ability to transform our lives.

Together with this significant growth, in the last years, it was a huge and yet increasing wireless networks and sevices deployment caused by the growth in the “Internet of Things” connectivity phenomenon[1], with wireless **M2M!** communications. ~~Being wireless communications nowadays one of the hottest and fastest growing segment of electronics.~~

This increasing demand for wireless communication ~~brought a remarkable~~ saturation on certains bands of the radio spectrum. This fact is mainly due to an inefficient assignment of the spectrum[2]. Some of the most heavily used bands are, for instance, unlicesed bands, free of cost, so-called ISM (*Industrial, Scientific and Medical*) bands.

Regarding spectrum scarcity, most WSN solutions operate on unlicensed frequency bands. Normally they use ISM bands, like the 2.4 GHz band, also used by Wi-Fi, Bluetooth or IEEE 802.15.4 devices.

The spectrum saturation is reflected over the increasing interferences and other undesirable effects as noise, with a consistent impact over [illegible]**K!** power required, QoS

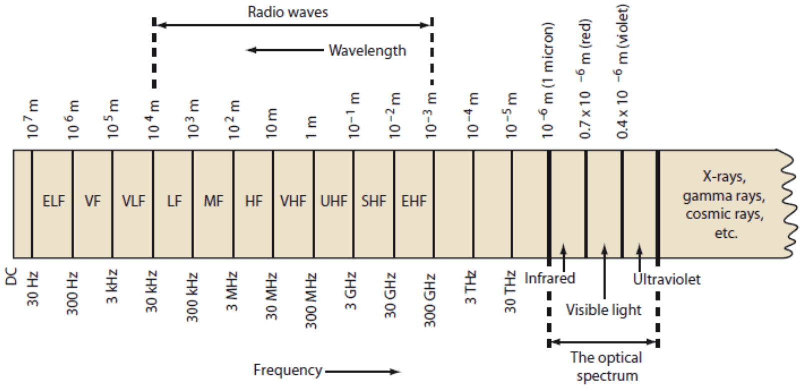


Figure 1.1: Electromagnetic frecuency spectrum. Radio spectrum covers under 300 GHz frequencies

(*Quality of Service*), etc. These troubles find their origin in the increasing amount of traffic, the heterogeneous networks and devices, ~~as well as~~ the inefficient use of the spectrum they do. Nowadays, techniques focused on expanding spectrum efficiency over communications, such as those related to dynamic channel allocation, power control or link adaptation, seem totally exploited and new long-term solutions are required.

To address this challenge, new techniques such as CR (*Cognitive Radio*) arise. CR was introduced by Mitola in 1999 [3] and 2000[4] and it integrates into communication networks concepts as spectrum sensing, self-learning, self-management or context analysis. Basically, CR enables opportunistic access to the spectrum through cooperation and context awareness. Spectrum sensing capabilities and cooperation among devices allow for better spectrum utilization and QoS. The concept of CN (*Cognitive Network*) describes a WN (*Wireless Network*) aware of its environment and able to adapt its communication parameters in order to achieve more reliable and efficient communications.

WSNs are shown as one of the areas with the highest demand for cognitive networking. Their imposed power consumption constraints and hard operation conditions require an efficient operation mode, specially in their wireless communications, since these ~~are normally~~ the most enery-consuming task. However, there are also ~~some~~ challenges to face[5] in opportunistic energy-efficient transport.

Despite the potential of CWSN (*Cognitive Wireless Sensor Network*), they are not deeply explored yet. Real or simulated scenarios scarcely exist and realistic platforms are crucial to the improvement and development of this new field. The shortage and undevelopment of CWSN devices or test-beds contributes to the scarcity of results in this area.

One of the current CWSN node platforms is the FCD (*First Cognitive Device*), developed in 2011[6] by researchers at the laboratory where this project is framed, the LSI (*Laboratorio de Sistemas Integrados*). The LSI belongs to the DIE (*Departamento de Ingeniería Electrónica*) within the ETSIT (*Escuela Técnica Superior de Ingenieros en Telecomunicación*) at UPM (*Universidad Politécnica de Madrid*). This laboratory hosts researching lines related to embedded systems, WSNs and security. The implemented device become the first real generic platform to study CWSNs hosting three radio transceivers, but it was just a first approach. The FCD was still far ~~to be really~~

valuable researching testbed platform. This platform did not fully satisfy requirements in terms of low power consumption, cost and size, and communication capabilities.

Continuing with the development of the FCD, some software implementation were carried out at LSI. A combined protocol stack for three different transceivers including a HAL (*Hardware Abstraction Layer*), described in [7], was created. This firmware offers to the application layers ease of use facing communication taks and it brings memory and resources savings compared with the previous three stacks based on protocol scheme. As well, in order to deal with cognitive strategoies and agorithmics, a software module that runs together with the application layer was launched. This module, called CRmodule (*Cognitive Radio Module*) implements the theoretical model described in [8] and it is a crucial achievement for CWSN development.

This dissertation describes the development and operation of the cNGD (*Cognitive Next Generation Device*), a node platform for CWSN development. It includes features and capabilities not found on current devices. cNGD must enable and promote CWSNs allowing test strategies and better investigation deployments. The final implementation must integrate the developed software modules HAL and CRmodule together with a demo application layer that show the full operation of the device.

1.2. Goals

The project main goal is to design and implement a node for a CWSN. The implementation must meet, regarding its utility, strong efficiency, modularity and scalability constraints. A demo application layer, also to develop, must integrate the already implemented HAL and CRmodule.

CWSN nodes are very limited devices in terms of memory, computational power or energy consumption. This fact is crucial and it must be taken into account, making the device valuable and affordable for researching purposes.

The design must be modular, so it will not need to be redone entirely with every particular change, and scalable, allowing flexibility in the complexity of applications. On the other hand, as development platform, the software and hardware architecture must provide advantages when implementing cognitive strategies as a valuable tool (data extraction, data reliability, portability, versatility...).

It is important to make clear that the design must fill the gaps and deficiencies that current devices show, providing a wider radio access, powering control options or real WSN features~~, for instance~~. Furthermore, a definition of new needs, together with an important review of the FCD is needed.

Here the main goal is fragmented into shorter subgoals:

- *Analysis of previous conclusions and results.* Study of already tested aspects. Definition of new tests to provide new data of interest. These data will help to take decisions about transceivers, microcontroller, power supply...

- *Requirements definition.* Study of needs and constraints (cost, resources, size, consumption...), according to the future running applications. Definition of features and requirements. Definition of the demo application.

- *Hardware design.* Pursuit of deficiencies over the FCD design and possible beneficial potentialities to achieve the new defined requirements. Design optimization. Components selection and final layout development.

- *Hardware debugging and implementation.* Component disposition and soldering. PCB design validation.
- *Application layer development.* Integration of the HAL and CRmodule into the hardware. Development of the demo application layer integrating the two already named software modules enabling a full test of the platform. The application will include tipical WSN functionalities.
- *General purpose tests.* Tests oriented to prove the proper operation and verify the achievement of the requirements and constraints compliance.
- *Results analysis and conclusions.* Evaluation of capabilities. Study of weaknesses or posible improvements. Definition of further studies.

1.3. Project Organization

The organization this project ~~has folled is here~~ described

- *State of art review.*

  At this first stage, CWSN~~s~~ related information and specific knowledge was acquired. Also, it was an approach to the development tools. Goals:

  - WSN and CR state of art review. Review of the current commercial solutions.
  - Adaptation to the developement platform as well as other tools (workstation, repository, soldering station, hardware at the lab...
  - Analisys of related projects results, either completed or under development.

- *Hardware design and implementation.*

  This phase covered from the first definitions and node specifications, to the system mounting and implementation. Goals:

  - Requirements definition and general node specifications. Stablishment of constraints and design criteria.
  - Radio wireless interfaces and other used components evaluation (microcontroller, serial interfaces...).
  - Design optimizations respect to the FCD.
  - Hardware full design. Selection of the components. Design adjustments and previous work verification. Layout design.
  - Hardware platform implementation.

- *Software design*

  Once the hardware was operating, the work turned over the software. Goals:

  - Integration of the developed HAL and CRmodule into the hardware.
  - Software implementation of required functions and application. Source code debugging.
  - Generation of first documentation about the developed software modules.

- *Tests and evaluation.*

  Finally the proper operation of the device was evaluated and its results analysed.

  - Fully integrated hardware and software test. Spectrum sensing, power consumption, autonomy and control, communication among nodes, connectivity to other devices, protocol stacks...
  - Results interpretation and conclusions review. Statement of further studies and future development lines. Found problems evaluation.

- *Documentation generation.*

  Dissertation and other required documentation (wiki, papers, manuals...) writing. Review of the software documentation.

1.4. Outline

Chapter 2

Cognitive Wireless Sensor Networks: State of Art

There's not much I know about you
Fear will always make you blind
The answer is in clear view
It's amazing what you'll find face to face

Thomas & Guy-Manuel, Daft Punk

This chapter shows an approach to the fundamentals of Wireless Sensor Networks and the current development state of new paradigms such as Cognitive Radio, Cognitive Networks or Cognitive Wireless Sensor Networks. It describes current related applications and implementations, and introduce terms used all along this dissertation.

2.1. Cognitive Radio

Nowadays, it is widely accepted that the main limitation in next-generation wireless systems is bandwidth scarcity. It is commonly believed that there is a crisis of spectrum availability for wireless communications[9]. However, according to regulatory bodies as the FCC (*Federal Communications Commission*)[10] or the Ofcom (*Office of Communications*), most radio frequency spectrum is under-utilized while some spectrum bands are heavily used. Military, amateur radio or satellital frecuencies, for instance, are insuffiently utilized compared to cellular networks or the overcrowded ISM bands[2].

Most of the spectrum is allocated to specific applications and the static assignment of the spectrum results in an inefficient use of it. Figure 2.1 shows how the actual utilization in the 3-4 GHz frequency band is 0.5 % and drops to 0.3 % in the 4-5 GHz band. This seems totally in contradiction to the concern of spectrum shortage.

Spectrum utilization depends strongly on time and place, however, fixed spectrum allocation prevents specific assigned frequencies from being used, even when this use would not cause noticeable interference to the assigned service. These facts lead to the current inneficiency situation where the utilization of the total spectrum can be considered around 10 % and more than 95 % of the use is below 3GHz.

Figure 2.1: A snapshot of the spectrum utilization up to 6 GHz in an urban area: taken at mid-day with 20 kHz resolution taken over a time span of 50 microseconds with a 30 degree directional antenna at Berkeley Wireless Research Center [11].

The concept of CR was first published by Joseph Mitola III and Gerald Q. Maguire, Jr. in 1999[3] and later on within Mitola's phD Dissertation in 2000[4]. It describes a novel paradigm for wireless communication in which a wireless device changes its transmission or reception parameters to communicate efficiently. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behavior, and network state. The idea was thought of as an ideal goal towards which a SDR (*Software-Defined Radio*) platform should evolve.

The cognitive radio is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of under- standing-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives:

- Hihighly reliable communications.
- Efficient utilization of the radio spectrum.

Although the concept of CR was defined originally as an extension to SDR[3], which is able to reason about external factors, recently the term is mostly used in a narrower sense. FCC suggests in [12] that any radio having the adaptive spectrum awareness should be referred to as CR:

> *"A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which is operates. The majority of cognitive radios will probably be SDRs (Software Defined Radios), but neither having software nor being field programmable are requirements of a cognitive radio."*

Attending to some subtle differences between systems we can differenciate two main different types of CR:

- *Spectrum-Sensing Cognitive Radio*, in which only the radio-frequency spectrum is considered.[13]
- *Full Cognitive Radio or Mitola radio*, in which every possible parameter observable by a wireless node is considered.[3]

Although cognitive radio was initially thought of as full cognitive radio, most research work focuses on spectrum-sensing cognitive radio, particularly in the TV bands. The great problem in spectrum-sensing cognitive radio is designing high-quality spectrum-sensing devices and algorithms for exchanging the so called knoledge domain [13]. The practical implementation of spectrum-management functions is a complex and multifaceted issue, since it must address a variety of technical and legal requirements.

Picture 2.2 ilustrates the changes the OSI (*Open Systems Interconnection*) model suffer when affected by cognition. CR model can be referred to the first and second layers, thus the *Phisical* and *Link* layers.

Figure 2.2: CWSN protocol model

The main functions of CR devices are:[14][15]

- *Spectrum sensing*: An important requirement is detecting unused spectrum and sharing it, without causing interferences to other users; Spectrum-sensing techniques may be grouped into three categories:
  - *Transmitter detection*: CR must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum. Enclosed here we can find approaches such as *matched filter detection, energy detection or cyclostationary-feature detection* are common.
  - *Cooperative detection*: Refers to spectrum-sensing methods where information from multiple CR users is integrated[16].
  - *Interference-based detection.* This technique is not so commonly used.
- *Power Control*: Power control is used for both opportunistic spectrum access and spectrum sharing CR systems for finding the cut-off level in SNR supporting the channel allocation and imposing interference power constraints for the primary user's protection respectively. In [17] a joint power control and spectrum sensing is proposed for capacity maximization.
- *Spectrum management*: Capturing the best available spectrum to meet user communication requirements, while not creating undue interference to other users. CR should decide on the best spectrum band (over the available range) to meet QoS requirements; therefore, spectrum-management functions are required for

CR. Spectrum-management functions are classified as *Spectrum analysis* and *Spectrum decision*.

Realizing that CR technology has the potential to exploit the inefficiently utilized licensed bands without causing interference to incumbent users, the FCC released a Notice of Proposed Rule Making which would allow unlicensed radios to operate in the TV-broadcast bands. The IEEE 802.22 working group, formed in November 2004, is tasked with defining the air-interface standard for wireless regional area networks (based on CR sensing) for the operation of unlicensed devices in the spectrum allocated to TV service [18].

Dynamic spectrum allocation has become a key research activity in wireless communications field and in particular a key technology for "The Network of the Future" objective proposed in ICT FP7[1].

2.2. Cognitive Networks and Cognitive Radio Networks

On the last years, "cognitive" or "smart" have become *trending topics* being applied to many fields, included to communication technologies. Having a look into the 90s literature, easily at least we find mentions about smart antennas[19], smart radios[20], smart packets[21], CR[3][13], cognitive packets[22] and CN[23][24]. Nevertheless, there does not seem to exist a commonly accepted definition of what these terms mean when applied to networking technologies.

The concept of CN has been hanging out the collective psyche of the networking and wireless researching field for long. The first approach was made by Mitola[3] when briefly describes how the CR could interact within the system-level scope of a CN. Saracco[25] talks about CNs in his investigation into the future information technology. Mahonen et al. [23] discuss CNs with respect to future mobile **IP!** networks. None of these previous references, however, express clearly what a CN is, how it should work and which problems it should solve.

The role that CR had in inspiring the formulation of CN concept, made, in some cases, CNs being described as networks of CRs[3][26]. Recent research can be divided into two categories: **CRN!** and CNs.

For **CRN!**, Mitola mentions how CRs could interact within the system-level scope of a CN[4]. Neel[27] and Haykin[13] continue this line of thinking, examinating multi-user networks of CRs as a game. The scope of **CRN!**s still remains primarily on MAC (*Medium Access Control*) and **PHY!** layers, but now operating with some end-to-end objective. In a **CRN!**, the individual radios take most of the cognitive decisions, although they may act in cooperation. Some suggested applications for **CRN!**s include cooperative spectrum sensing[28][29] and emergency radio networks [30]. Raychaudhuri presents in[31] a general architecture for **CRN!**s.

Regarding CNs, Clark proposes, in which was perhaps the first mention of CN rather than **CRN!**, a network that can

> "assemble itself given high level instructions, reassemble itself as requirements change, automatically discover when something goes wrong, and automatically fix a detected problem or explain why it cannot do so."

[1] Framework Programmes for Research and Technological Development are funding programmes created by the European Union in order to support and encourage research in the European Research Area (ERA).

This would be achieved with the use of a **KP!** that transcends layers and domains to make global cognitive decisions. The **KP!** will add intelligence and weight to the edges of the network, and context sensitivity to its core. Saracco stated[25] that the change from network intelligence controlling resources to having context sensitivity will help "flatten"the network by moving network intelligence into the core and control further out to the edges of the network. **CRN!**s differ from CNs in that their action space extends beyond the MAC and **PHY!** layers and the network may consist of more than just wireless devices. Furthermore, CN nodes may be less autonomous than a CRN node.

First full definition of CN was postulated by Thomas[32] in which was his PhD Dissertation. Hi proposed the idea of a CN:

> *a network composed of elements that, through learning and reasoning, dynamically adapt to varying network conditions in order to optimize end-to-end performance. In a CN, decisions are made to meet the requirements of the network as a whole, rather than the individual network components.*

The adaptations that are performed over usual networks are commonly reactive, taking place after a problem has occurred. Thomas advanced a paradigm that had the promise to remove these limitations by allowing networks to observe, act, and learn in order to optimize their performance. CNs description in [32] talks about intelligently select and adapt radio spectrum, transmission power, antenna parameters and routing tables. By formalizing the design, architecture and tradeoffs of cognition at the network level, Thomas work had a broad impact in advancing the paradigm of intelligent communication devices.

2.2.1. Example

This example was published [32] in and it is inspired and influenced by Daniel Friend's example in [33]. It illustrate the need for end-to-end rather than link adaptations.

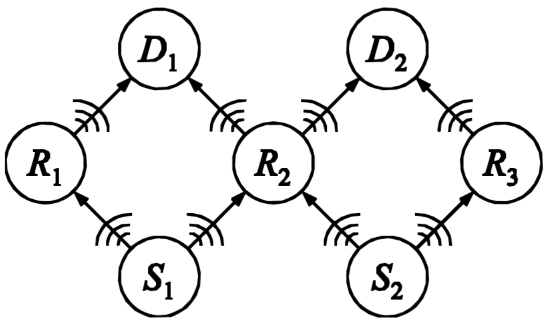


Figure 2.3: Simple relay network for a wireless network. Vertices represent wireless connectivity

Consider an ad-hoc data session between a source node S_1 and a destination node D_1 as shown in Figure 2.3. The source node does not have enough power to reach D_1 directly, so it must route traffic through intermediate nodes R_1 and-or R_2. Assume that the end-to-end goal is to have the highest probability of successful transmission. The routing layer will determine routes based on minimum hop count which, in this case, includes either R_1 or R_2. Node S_1 will make a link-layer adaptation, selecting between R_1 and R_2 based on their **SINR!**. From the standpoint of the link layer in node S_1, this ratio correlates with the probability that the transmitted packets will arrive correctly at the relay node. However, without additional information, this selection does not guarantee anything about the end-to-end packet delivery probability from S_1 to D_1. In contrast to a link adaptation, the CN might use some combination of observations from all nodes to compute the total path outage probabilities from S_1 to D_1 through R_1 and R_2. This shows the benefit of an end-to-end scope, but there is another advantage to the CN, its cognitive capability. To illustrate this, we modify the original scenario to include both S_1 and S_2 as source nodes, both routing traffic through R_2. Suppose that the learning mechanism measures outages by determining the fraction of packets successfully delivered from the source to its destination.

If R_2 becomes congested because of a large volume of traffic coming from S_2 this becomes apparent to the cognitive process by the lack of successful packet delivery statistics provided to S_1 and S_2. The learning mechanism recognizes that the system has changed and that routing through R_2 is not optimal. The cognitive process then directs the traffic toward another route. The CN does not explicitly know that there is congestion at node R_2 because this information is not included in the **SINR!** observations. Nevertheless, it is able to infer from the reduced throughput that there may be a problem. It is then able to respond to the congestion, perhaps by routing traffic through R_1 and/or R_3. This example shows the power of CNs in optimizing end-to-end performance as well as reacting to unforeseen circumstances.

2.3. Wireless Sensor Networks

A WSN consists of spatially distributed autonomous "nodes" not relying on a pre existing communication infrastructure, to monitor physical or environmental conditions. Number of nodes vary from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Nodes are generally simple and low-resources embedded system with high cost and size constraints. These constraints result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth. Usual architecture of a node is divided in:

- *Sensing subsystem.* Responsible for sensing physical parameters of the environment. Typical monitored parameters are temperature, sound, light, humidity, vibrations, pressure, movement, presence, body registers...
- *Computational subsystem.* It proccess the information obtained by the sensors and process it. It controls all general operations of the node, and runs the desired application.
- *Communication subsystem.* To carry through all the messages transmission and reception with neighbor nodes. Main goal is to make the information gets to some destination, usually a gateway or storaging node.

The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in a wide range of

Figure 2.4: WSN node model

applications, considered as the main technology to develop intelligent ambiences:

- *Industrial Monitoring.* WSN are applied mainly for machine health monitoring, water quality or management, and industral sense and control applications avoiding wire deployment.
- *Surveillance.* Distributed sensors over infrastructure as bridges, tunnels or buildings help to collect data to prevent damages or problems derivated from load excesses, weather, vibrations or stress.
- *e-Health.* Not deeply explored yet. It presents new uses for WSN to sense body parameters and observate behavioral patterns. These networks are used to detect or prevent occupational and home accidents, to improve diagnoses, monitoring sick people and other medical uses.
- *Environmental monitoring.* Applications regarding this fiel are diverse. Air quality monitoring, air pollution monitoring, forest fire detection, landslide detection, water quality monitoring or natural disaster prevention are some of the common uses.
- *Smart home monitoring.* Monitoring the activities performed in a smart home is achieved using wireless sensors embedded within everyday objects. State changes to objects based on human manipulation is captured by the WSN enabling activity-support services.
- *Passive localization and tracking.* Applications oriented to detect where something took place or track presences over an area.
- *Agriculture.* Commonly used on greenhouses where irrigation management and ambient control is essential for a proper accurate agriculture.

Some of the main properties affecting WSN are:

- *Dinamic topology.* In a WSN it is common to suffer drops in the number of nodes or changes over the environment that affects the topology, nodes must be able to adapt themselves to new topologies to enable operative communications. On the same way, topologies must be scalables since a network might have tens of nodes or hundred of them.

- *Autonomous operation.* There is not need any infrastructure for a WSN to operate. Its nodes act as information transmitters, receivers or routers. However, it usually exists a gateway which gather all the information over the network and pass it to another device.

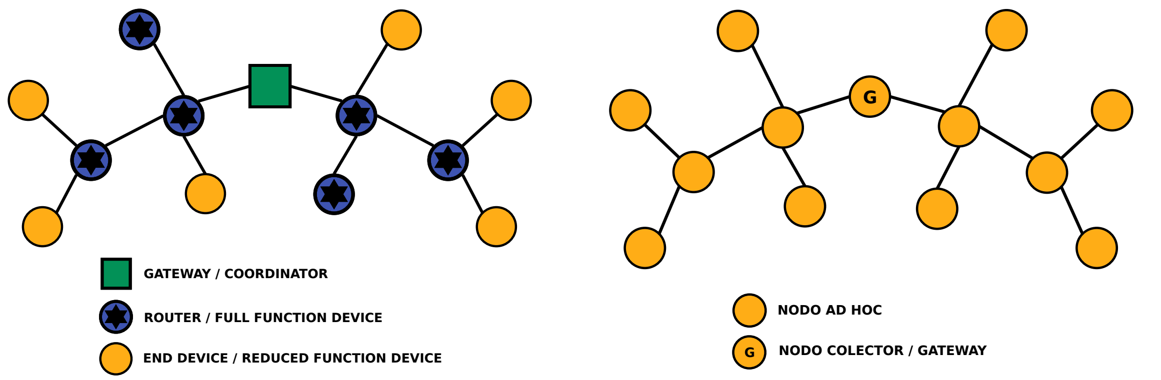
- *Multihop or broadcast communications.* It is common the use of some protocol to enable multihop messaging. Nevertheless, broadcasting is also very expanded.

- *Power consumption.* One of the most important factors. Using a very constrained amount of energy, devices must achieve a tradeoff between autonomy and troughput. A WSN node must meet a low-consumption microcontroller, as well as radio interfaces and software equally featured.

- *Hardware constraints.* In order to achieve a low-power consumption, it is essential for the hardware to be as most straightforward as possible, coming into a limited computing capability.

- *Production costs.* Since WSNs nature implies having a high number of nodes to be trustable, production of large amounts of them must provide a cheap unitary price.

Most important communication techonologies and protocols for WSN are based on the IEEE 802.15.4 [34] standard for WPAN (*Wireless Personal Area Network*)s. The standard goal is a low-power communication among nearby devices without underlying infrastructure. The standard only defines MAC and **PHY!** layers of the OSI model. Some expanded protocols based on the standard are ZigBee^{TM} *****REF, WirelessHART*****REF, ISA100.11*****REF or MiWi^{TM}**********REF specifications. Another popular communication standard is IEEE 802.11***** REF, in which is based WiFi*****REF. It is a **IP!** standard based on the final user and does not meet low-consumption constraints, however, convergence towards full **IP!** has brought new standards such as **6LOWPAN!** *****REF, that enables **IP!** packeting over 802.15.4 based-on networks.



(a) WSN con utilización de routers para la conexión con el gateway.

(b) WSN implementada como una red ad hoc.

Figure 2.5: Possible WSN implementations.

2.4. Cognitive Wireless Sensor Networks

CWSNs arises as a natural evolution of traditional WSNs since IEEE standards used in WSNs already postulate access to several bands of the spectrum. Additionally, QoS and low-consumption requirements that WSNs state, fits the goals of CR. Currently, ISM bands, where most of WSNs place their radio activity, show an overcrowded scene where CR techniques might significantly help the newtork operation. Applying cognitive capabilities seeks intelligent adaptations based on learning, reasoning and information sharing among multiple nodes in the network to achieve end-to-end goals. Thus, these techniques, based on distributed intelligence, contribute to improve performance of the network over an extended period of time even in the presence of conflicting goals.

Basically, CR and CN techniques applied into WSNs leads to CWSNs. This idea suposses an increment of complexity over the executed algorithms and overload the control data flow over the network. Cognitive agents capable of making proactive decisions based on learning, reasoning and information sharing when interspersed in sensor networks, may help achieve end-to-end goals of the network even in the presence of multiple constraints and optimization objectives. Cognitive radio at the physical layer of such agents may enable the opportunistic use of the heterogeneous wireless environment.

Cognitive communication in a sensor network could not only help meet end-to-end goals of the entire network, but also increase reliability of the network, reduce maintenance costs and increase the network lifetime. Research in [35][36][37][38]suggests the growing interest in applying cognitive techniques to WSNs. The idea of a holistic approach to introducing cognition in heterogeneous sensor networks that combines the advantage of opportunistic spectrum access at the physical layer, with cognitive communication among sensor nodes seamlessly across the network promises to be advantageous over existing design techniques.

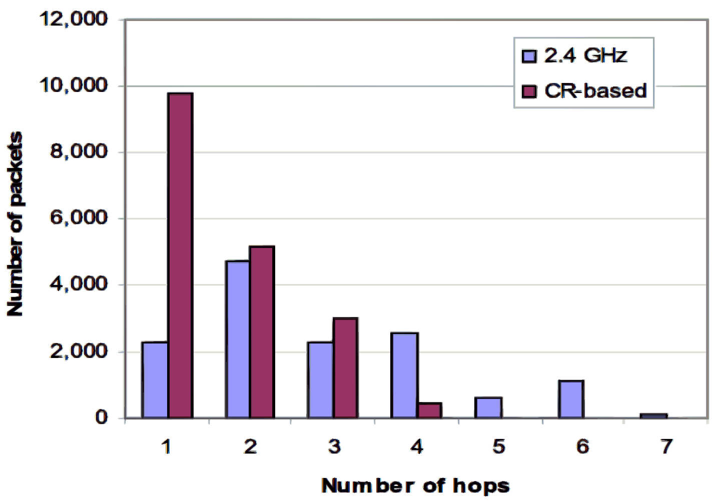


Figure 2.6: Number of hops per packet comparison in a CWSN simulated scenario described in [38]

However, research efforts have been discrete and cognitive techniques have focused on improving specific aspects of the network or benefiting specific applications.

Vijai contributes[39] to CWSN giving the vision and advantage of a holistic approach to cognition in sensor networks. It also provides a framework based on knowledge and cognition.

In [8] oportunities and trends arising from networks and nodes cooperation are mentioned. It is seen as a chance to improve general features and dynamic adaptation capabilities. [8] proposes an implementation model based on agents carrying out basic functions and keeping a **VCC!**. This **VCC!** takes part on the **KP!** that agents use to exchange gestion messages.

On the other hand, applying cognitive techniques involving artificial intelligence and game theoretic approach to increase knowledge in the system has several challenges.

- As stated in [40], nodes may be cheating or be constrainned about their valuations, i.e., communicating an agent's valuation for a large subset of the resources might become infeasible. Establishing the feasibility of integrating CR into the DSA (*Dinamic Spectrum Access*)[41] scheme at the physical layer, along with cognition in upper layers to achieve end-to-end performance goals is an open research problem.
- For such networks to be justifiable, the performance improvement must outweigh the cost in terms of overhead, architecture, and operation. An analysis on the amount of energy expended in information sensingn and communicating the same to neighboring nodes is essential in establishing the suitability of this approach.
- Since the information available to the network may be partial or incorrect, it may lead to security issues and hence, issues and techniques to deal with such issues must also be identified.
- The proposed cognitive nodes could be statically distributed in the network or could be mobile, gathering information from remote locations of the sensor nodes. Hence, deciding on the optimal deployment architecture of the cognitive capability is also a challenging problem.
- Protocols that define how the knowledge plane can be implemented to seamlessly access information from the end user and use it to make decisions at the physical layer, the cognitive specification language, and the tools used in cognitive decision making must all be standardized to make such networks interoperate.

All in all, this early-staged technology claims for investigations and research-enabling implementations such as standars, simulators and test-beds that allow further studies and conclusive results.

2.4.1. Current Devices

Because of the novel stage of this research field, there are not many specific devices to build applications and services over CWSNs. Besides, current implementations find themselves very poorly featured yet, not responding researchers'requirements. It is natural that most works are based on WSN platforms on one side and SDR platforms on the other side.

There are many different kinds of devices for WSN platforms with similar characteristics: low power, memory and processing constraints, and ISM bands. Bean, BTnode, MANTIS Nymph, IMote, MicaZ, SenseNode, XYZ, Sentilla Mini, TelosB [11]****REF, ANT [12]****REF, EyesIFX [13]****REf and Iris [14]****REF are some of the most important WSN devices. But none of them have different radio interfaces or radio reconfiguration capabilities.

There are many SDR platforms that have been developed to support individual research projects. Berkeley Cognitive Radio Platform [7]****REF (del paper) (based around the BEE2[2]), OpenAirInterface [9] *** REF (proposed by the mobile communications department at EURECOM), NICT[3] SDR platform [6]****REF (del paper), the Kansas University Agile Radio (KUAR) [8]****REF, or the Universal Software Radio Peripheral (USRP) [10]***REF are the most important ones.

In order to evaluate CWSN models and architectures, great efforts have been carried through developing simulators or adapting traditional simulators to new schemes. Nevertheless, test-beds allow to test real systems, obtaining data about consumption, radio transmission ranges, error rates and providing trustable feedbacks to improve simulators performance. Here it is made a review over existing software and hardware platforms.

2.4.1.1. Software platforms - simulators

Some of the main characters over the existing simulators range are:

- *NS2/NS3*. *****REF From Network Simulator. NS is a discrete-event network simulator primarily used in teaching and research. It supports a large variety of multicast and unicast protocols of both wireless and wired networks. Intesively used in wireless mobile Ad-hoc networks. NS simulators are developed mainly under C++ and Python languages and they are publicly available under the GNU GPLv2 license for research, development, and use. Last stable version

(a) NS2 Simulator Logo. (b) NS3 Simulator Logo.

Figure 2.7: NS2 and NS3 Simulators Logo.

Currently, NS2 scource code consists of many forks, both maintained and unmaintained. Last version, from 2009, is partially maintained but not being considered for journal publications. It runs on GNU/Linux, FreeBSD, Solaris, Mac OS X and Windows 95/98/NT/2000/XP. NS3 would be written from scratch, not being compatible with NS2 generally. Development of NS3 began in July 2006. The first release, NS 3.1 was made in June 2008, and afterwards the project continued making quarterly software releases, and more recently has moved to three

[2]Berkeley Emulation Engine system is designed to be a modular, scalable FPGA-based computing platform
[3]Japanese National Institute of Information and Communications Technology

releases per year. NS3 made its fifteenth release (ns-3.15) in the third quarter of 2012 and it is actively developed.

Libraries and packages for cognitive simulation and development exist for these simulators, however, models, parameters, and results are still quite poor and inaccurate.

- *OMNeT++.* /******REF It is not a simulator itself but rather an extensible, modular, multiplatform, component-based C++ simulation library and framework. Instead of containi A real time cognitive radio testbed for physical and link layer experimentsng explicit and hardwired support for computer networks or other areas, it provides the infrastructure for writing such simulations. OMNeT++ provides a component architecture for models. Components (modules) are programmed in C++, then assembled into larger components and models using a high-level language (NED). These models, most of them opensource, are developed completely independently of OMNeT++, and follow their own release cycles. They cater domain-specific functionalities, such as support for sensor networks, wireless ad-hoc networks, Internet protocols, performance modeling, photonic networks. There are extensions for real-time simulation, network emulation, alternative programming languages (Java, C#), database integration, SystemC integration, and several other functions.

  Figure 2.8: OMNeT++ Simulator Logo

  CWSN simulations over OMNeT++ are possible thanks to MiXiM. MiXiM is an OMNeT++ modeling framework created for mobile and fixed wireless networks (wireless sensor networks, body area networks, ad-hoc networks, vehicular networks, etc.). It offers detailed models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols. It is a merger of several OMNeT++ frameworks written to support mobile and wireless simulations. The predecessors of MiXiM are ChSim, Mac Simulator, Mobility Framework and Positif Framework.

- *Castalia.* **** REFIt is a WSN simulator based on OMNeT++ for early-phase algorithm/protocol testing built at the Networks and Pervasive Computing program of National ICT Australia since 2006. Since 2007 it is made public as an open source project under the **APL!** license The current release version is 3.2. It supports realistic channel and radio models, a key element for accurate early-phase WSN simulation. It provides support for defining versatile physical processes for specific applications, since it is highly parametric, and can simulate a wide range of platforms. It also supports enhanced modeling of the sensing devices and other often-neglected attributes of a WSN such as node clock drift[4].

  Castalia support for CWSN was first proposed by researchers from LSI at Plytechnic University of Madrid **** REF in 2012.

[4] Clock drift refers to several related phenomena where a clock does not run at the exact right speed compared to another clock.

Figure 2.9: Castalia Simulator Logo

- *NetSim.* NetSim is a stochastic discrete event simulator developed by Tetcos, in association with Indian Institute of Science, with the first release in June 2002. This popular network simulation tool used for network lab experimentation and research. Various technologies such as WSN, Wireless LAN, WiMax, TCP, IP are supported. NetSim comes with an in-built development environment, which serves as the interface between User's code and NetSim's protocol libraries and simulation kernel. Protocol libraries are available as open C code for user modification.

Figure 2.10: NetSim Simulator Logo

Some libraries available for NetSim enables CR capabilities for simulations. However, these cognitive libraries are focused on applications for 802.22 WRAN based cognitive radio networks, which make this simulator undesirable for CWSN scenarios.

- ***SENDORA!***.****REF SENDORA project developed in 2010 suppossed a new approach of CR called Sensor Network aided Cognitive Radio. This project was led by Thales, Eurecom, NTNU, Telenor, KTH, TKK, Universities of Rome, Valencia and Linköping. It was divided into 8 work packages taht covered from to management activities to dissemination passing through definition, integration, implementation and demonstrations activities. Software based on the NS simulator was developed and hardware operating over VHDL language.

Figure 2.11: SENDORA Simulator Logo

The SENDORA project brought a high amount of papers and literature, nevertheless, the software developed has come shifted to the background because of other simulators. Regarding hardware implementations, carried out over **FPGA!**, revealed useful data but not real devices. Hence, simulations deployed do not use real device data for the power model.

Several other simulators have been developed for WSN. TOSSIM based on the TinyOS[5] operative system, COOJA, OPNET, GloMoSim, JSim, NetSIm or QualNet are more WSN simulators without cognitive features despite some approaches and efforts to create frameworks enabling them.

2.4.1.2. Hardware platforms

Nowadays there are not real devices for CWSN applications yet. Current implementations respond to development platforms or test-beds and still, variety of platforms is very scarce and poorly featured. Most of them suppose the first approaches on its field, so foundations to build over are still inmature and quickly changing. Hence, efforts focussed on hardware development, usuallyl more costly than software, remain quiet.

The closest existing device to a CWSN node is the FCD[6][42] developed at LSI in 2011. The FCD is based on a Microchip 32-bits PIC (*Peripheral Interface Controller*) and includes three radio interfaces enabling access to the 2.4 GHz band and 868 MHz. MiWi and WiFi protocols operate over 2.4 GHz and a propietary protocol provided by AWD (*Advanced Wireless Dynamics*)[6] operates over 868 MHz. The device gave the chance to develop and test algorithms, strategies and and applications for CWSN. Moreover, it allowed to analyse suitability for radio interfaces, computating capability. It gave the strengths and weaknesses to stablish the fundamentals on future designs. Nevertheless, the device still but it was just a first approach and it was still far to be a stable commercial testbed platform. The node did not fully satisfy requirements in terms of low power consumption, cost and size, and communication capabilities.

Consecutively, new hardware and software modules were incorporated to expand its features. These modules included a expansion board to try new transceiver options together with an optimized,CWSN oriented firmware and a cognitive software module. This new modules claim for a new design integrating togethe all of them at one single module, fixing detected weaknesses and adding new or improved features.

Other deployed CWSN devolpment networks placed at researching centers, so called test-beds, are employed to obtain data and try algorithms to feedback simulators and node devices themselves. Here mentioned test-beds do not include nodes with access to several radio bands, but rather several kind of nodes having different interfaces each. Hence, not real CWSN nodes are implemented. Main current test-beds are:

- *TWIST (TKN Wireless Indoor Sensor network Testbed)*. *****REF Developed by the **TKN!** at the **TU!** Berlin, is one of the largest academic testbeds for experimenting with wireless sensor network applications at indoor deployment scenarios. It provides basic services like node configuration, network-wide programming, out-of-band extraction of debug data and gathering of application data, as well as several novel features such as active power supply control of the nodes. The self-configuration capability, the use of hardware with standardized interfaces and open-source software makes the TWIST architecture scalable, affordable, and easily replicable. TWIST can be accessed locally or remotely via web interface.

[5]TinyOS, started as a collaboration between the University of California in co-operation with Intel Research, is a free and open source software component-based operating system and platform targeting WSNs).

[6]A radio interface developed by AWD, a spin-off originated at LSI, oriented on solutions for energy efficiency, industrial control and intelligent environments.

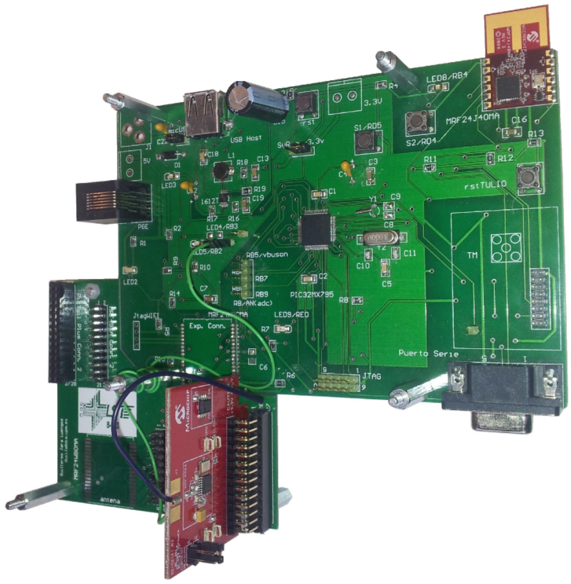


Figure 2.12: Picture of First Cognitive Device expanded

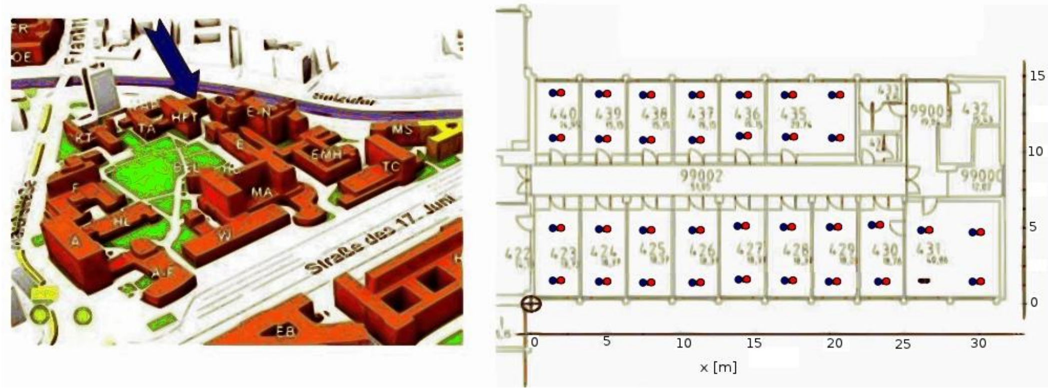


Figure 2.13: 1 floor deployment of TWIST test-bed

It spans the three floors, more than 40 rooms, of an office building at the TU Berlin campus, resulting in more than 1500 m^2 of instrumented office space. Currently the setup is populated with 102 TmoteSky**** REF nodes operating over 2.4 GHz and 102 eyesIFX**** REF nodes over 868 MHz resulting in a fairly regular grid deployment pattern with intra node distance of 3m. A set of low-cost USB WiSpy Spectrum Analyzers for the 2.4 GHz band dig over data and store it on a repository, this information is used as data-base for the CR algorithms and spectrum use optimization.

- *VT-CRONET (Virginia Tech COgnitive Radio NEtwork Testbed)* ** REF It is a collection of CR nodes deployed throughout a building on the Virginia Tech main campus. The testbed is openly available for the purposed of performing advanced **CRN!**. The testbed consists of a total of 48 static SDR nodes based on

USRP2[7], located in the ceiling throughout the ICTAS building, being placed 12 nodes per floor. In addition to the static nodes, low-power mobile nodes will also be available in order provide a research environment that accomodates a wide variety of research topics.

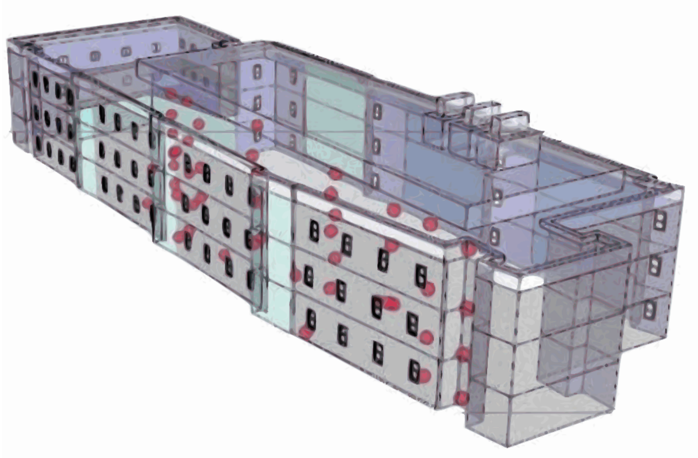


Figure 2.14: Deployment of VT-CORNET test-bed

Remotely accessible, emphasis is on cognitive engine design, self-organizing networking algorithms, and network security. The testbed enables researchers to implement and test their algorithms, protocols, applications, and hardware technologies within a realistic environment.

- *LOG-a-TEC.* LOG-a-TEC covers a set of diverse testbeds used for research purposes. The testbeds are mostly based on the VESNA****REF hardware platform - developed by SensorLab. The testbeds currently consist of 70-80 sensor nodes installed outdoors, mostly on light poles and rooftops in different regions of Slovenia. They allow remote monitoring, reconfiguration and experimentation. The application area range from environmental monitoring, smarts grids to cognitive radio experimentation.

- *FIT/CorteXlab - Cognitive Radio Testbed.* This testbed, still under deployment, will be hosted at INSA-Lyon in France. CorteXlab will suppose one more researching center of the Future Internet of Things project****** REF. CorteXlab will use the network architecture developed in SensLAB and will integrate SDR nodes to offer a remotely accessible development platform for distributed CR. Reconfigurability, compatibility, coexistence and even cooperation between SDR nodes will be evaluable. A large set of heterogeneous SDR nodes (**MIMO!** nodes, **SISO!** nodes and WSN nodes) together with classical sensor nodes will permit a full experimental evaluation.

  The testbed will be installed in 180 m^2 shielded room (isolated from any external interference) and also partly covered with **EM!** absorbing material. Depending on the set of enabled frequencies, the design of the room will enable to control

[7]The **USRP!** family features a modular architecture with interchangeable daughterboard modules that serve as the RF front end.

Figure 2.15: CorteXlab testbed logo

the radio channel characteristics (number of paths, delays, etc...) and to ensure a high level of reproducibility of experimentations.

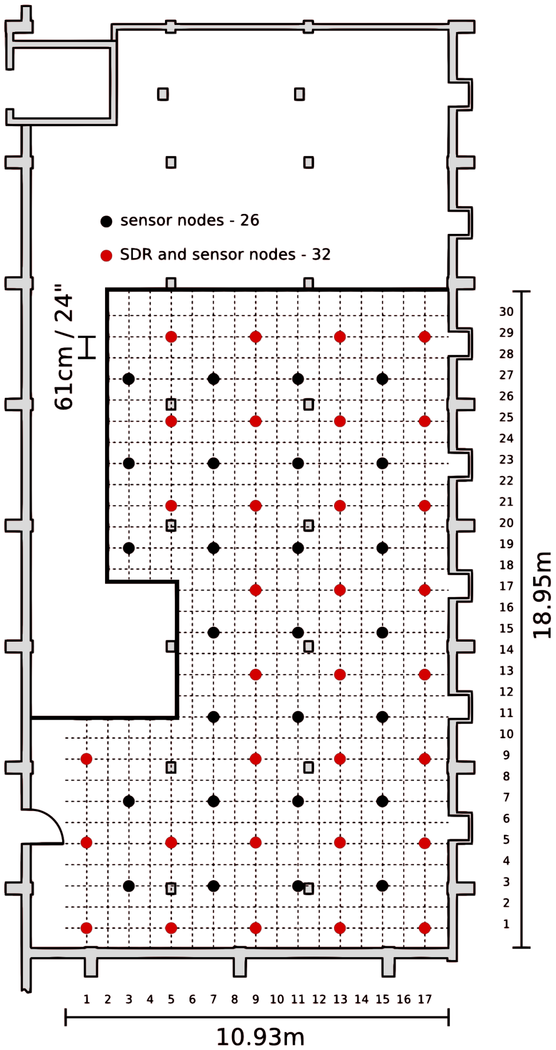


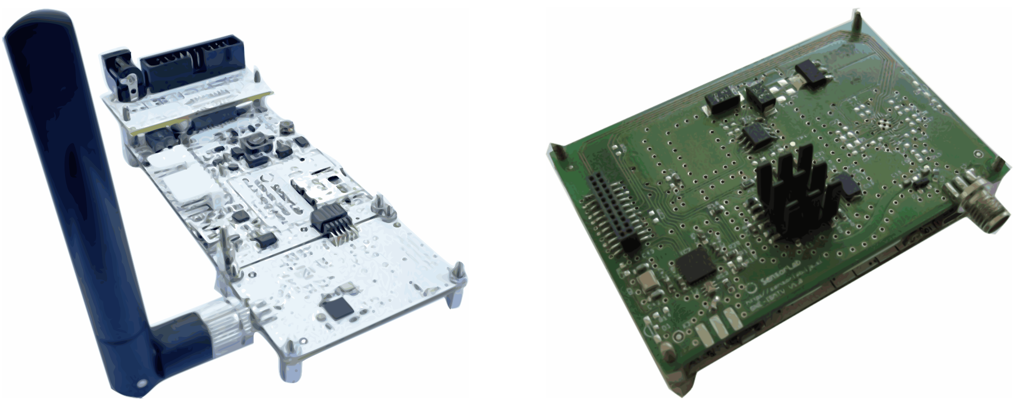
Figure 2.16: CorteXlab testbed deployment

Nodes will be uniformly distributed. These nodes will be able to accept **PHY!** layer implementations on both hardware, i.e. **FPGA!**, and software on general purpose CPUs. Furthermore, they will be capable of outputing performance metrics, such as throughput, **BER!** and power consumption. The nodes are interconnected through a high speed ethernet link, in order to allow for cooperation and sharing of information. A unified server will also be available for starting, coordinating and collecting the results of experimentations. The experimentation themselves can be from **PHY!** layer up, including the possibility of cross-layer interactions.

All in all, CWSN nodes share common features with standard WSN nodes. Particullary, CWSN nodes must offer additional features such as certain frequency agility. It exists some devices, not CWSNs-oriented but meeting this frequency agility. The most importants:

- *VESNA*. **** REF WEB It is a modular and fully flexible platform for the development of WSN developed by SensorLab @ Jozef Stefan Institute. Based on the high-performance microcontroller with ARM Cortex-M3 core and radio interface spanning over multiple ISM frequency bands it is designed to meet the requirements of diverse applications. In terms of modularity the platform consists of the VESNA core module and a set of special feature modules (sensor node radio - SNR, sensor node expansion - SNE, sensor node power - SNP) that are used as/if needed. Various peripherals including UART, I2C, SPI, USB, ADC and DAC allow hosting of different sets of sensors and/or actuators.The platform readily supports:

  - Communication standards IEEE 802.15.4, IEEE 802.15.1 and IEEE 802.11.
  - ZigBee, 6LoWPAN, Bluetooth and Wireless M-Bus protocol stacks and technologies.
  - Operating system Contiki[8].
  - Connection to the Internet via Wi-Fi, Ethernet or GSM/GPRS;
  - Arduino integrated development environment.
  - A variety of energy supply options including battery, solar panel and external power supply.



(a) Picture of VESNA.

(b) Picture of SNE-ISMTV-UHF (top) mounted on a VESNA sensor node (bottom).

Figure 2.17: Pictures of SNE-ISMTV and VESNA modules.

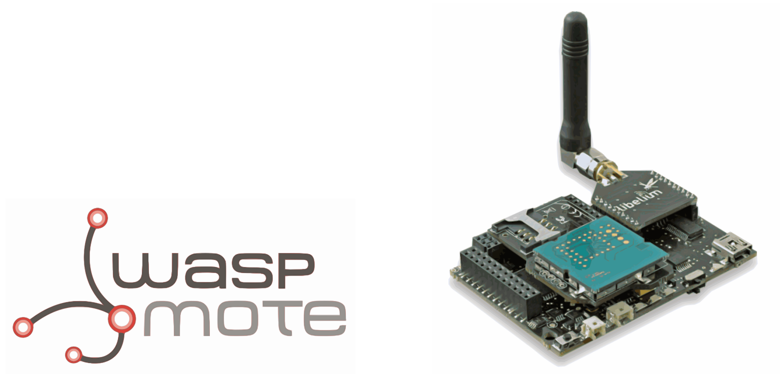
[8]Contiki is an open source operating system for networked, memory-constrained systems with a particular focus on low-power wireless Internet of Things devices.

To enable CR capabilities on VESNA, a radio front-end was developed, the SNE-ISMTV****REF. Different versions were capable of operating in three frequency bands of interest (TV broadcast part of the UHF band, 868 MHz and 2.4 GHz ISM band) and flexible enough to enable various user scenarios.

SNE-ISMTV-UHF contains a VHF and UHF TV band receiver based on the NXP TDA18219HN silicon tuner and was designed for spectrum sensing experimentation in TV white spaces. SNE-ISMTV-UHF can receive signals from 470 to 870 MHz with channel filter bandwidths between 1.7 MHz and 10 MHz. Using an analogue detector with a logarithmic response it can be used for energy detection experiments with the resolution bandwidth identical to the channel filter setting and approximately 50 ms per channel sampling. The detector is also coupled with an A/D converter optionally providing 1 Msample/s of the amplitude of the baseband signal. The samples can then be further digitally analyzed in software on the sensor node for more advanced spectrum sensing methods.

SNE-ISMTV-868 and SNE-ISMTV-2400 are based on the TI CC1101 and TI CC2500 integrated circuits respectively and are identical in design and operation except for the supported frequency band. These transceivers contain software-reconfigurable radio front-ends operating from 780 and 930 MHz and from 2.40 to 2.48 GHz with channel bandwidths from 60 to 800 kHz and frequency-agile local oscillators with 75 ms settling time. They include an ntegrated logarithmic detector for energy detection and several modems that can be either connected to integrated packet handling hardware or provide a raw baseband digital stream to and from the CPU. This makes it possible to support experiments that require packet based as well as continuous transmissions.

- *WaspMote*. It is an ultra low-power consumption a sensor node developed and marketed by Libelium[9] based on an ATmega1281 microcontroller. It provides a socket for radio interfaces and several standarized input/output options. Libelium offers up to 60 different sensor expansion boards and 6 different radio options. An attachable board enables connection for two radio interfaces. It is thought to be a versatile node valid for a wide range of WSN applications.

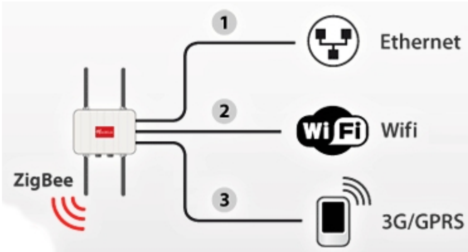


(a) WaspMote Logo. (b) Picture of Libelium WaspMote.

Figure 2.18: Libelium WaspMote.

[9] http://www.libelium.com

- *Meshlium.* Meshlium, also from Libelium, works as the Gateway of the Waspmote SN (*Sensor Network*). It reads the sensor frames coming from the nodes and store them in its internal data base and in external cloud systems located on the Internet. The frames coming from Waspmote are normally received by the 802.15.4/ZigBee radio and sent to the Internet using Ethernet, WiFi and 3G interfaces.



(a) Meshlium operation mode.

(b) Picture of Libelium Meshlium.

Figure 2.19: Libelium Meshlium.

Standardization is at the core of the current and future success of cognitive radio. The IEEE 802.22***REF WIKIPEDIA working group is developing what will be first cognitive radio-based international standard for **WRAN!** with tangible frequency bands for its operation. It will operate on unused television channels. One system such as Unlicensed-Band Cognitive Radio, which can only utilize unlicensed parts of the **RF!** spectrum, is described in the IEEE 802.15 Task Group 2 specifications***REF WIKI. This standard focus on the coexistence of IEEE 802.11 and Bluetooth. Many other standards such as WiFi (IEEE 802.11), Zigbee (IEEE 802.15.4), and WiMAX (IEEE 802.16) already include some degree of CR technology today.

It has shown how CWSN is still an inmature researching field where scarce devices, and all of them incomplete, are found. Real and complete devices to allow developers to try security, energy and spectrum optimization, and QoS algorithms and strategies are needed. Facing this need, LSI proposes the implementation of a complete development platform, hardware and software, fully oriented to CWSN investigation able to truly simulate real WSN applications. Fulfilling WSN, cognition and development requirements. This goal define and frames this Master Thesis.

Chapter 3

Review Study

Work It Harder Make It Better
Do It Faster, Makes Us stronger
More Than Ever Hour After
Our Work Is Never Over

Thomas & Guy-Manuel, Daft Punk

In this chapter it is defined a model for our cognitive node. Firstly, the First Cognitive Device is evaluated to obtain some guidelines and potential improvements in our design. The final device implementation requirements and constraints are defined. Finally, it is carried out a discussion and evaluation about different modules, exposing different commercial options and coming into final decissions.

3.1. Cognitive Wireless Sensor Network Node Model

Basically, the CWSN node scheme responds to a standard WSN model based on a microcontroller, radio and sensor interfacing, and power supply. However, a further review shows some general differences:

- *Multiple Radio Interfacing*: Regarding CR capabilities for spectrum management and DSA, the node must include multiple radio interfaces enabling different spectrum bands instead of a signle one. This capability is referred to the hardware modules.
- *Multiple Control/Sensor Interfacing*: Since the device will serve as a standard CWSN platform, it must embbed different multi-purpose undefinned interfaces[1]. This fact affects the hardware design of the device.
- *Protocol Stacking*: In order to enable communication over the different interfaces the model, must provide proper access to a the lower layers of a communication protocol to each radio interface[2]. The final implementation firmware will have to take part of this.

[1]The interfaces here mentioned cover the usual peripherals and buses such as I^2C (*Inter-Integrated Circuit*), SPI (*Serial Peripheral Interface*), UART (*Universal Asynchronous Receiver-Transmitter*), USB (*Universal Serial Bus*)...

[2]As it will be described, the communication protocol stack supposses a great software development in order to maintain a single stack shared by all the interfaces.

- *Cognitive Layer*: To carry out all the cognition algorithms and computations. Affecting the firmware.

Figure 3.1: CWSN node model

Figure 3.1 gives a view about the basic model. It shows together software and hardware modules in a simplified way. Additionally, cognition tasks compulsory require of several functions to take into account at the design stage:

- *Power management*. Efficiency and low-power comsupmtion are crucial following the inherent trend in WSN. Once deployed, is common not having or having barely access to the nodes. Replacing batteries to an entire WSN comes to be a kafkaesque task. The model should be able to include an autonomous power supply and other functions:
  - Transmission/reception power regulation.
  - Unused modules disconnection.
  - Power-saving sleeping modes for transceivers and microcontroller[3].
- *Spectrum management*. Some of the main functions to carry through:
  - RSSI (*Received Signal Strength Indication*) detection.
  - Channel switching
  - Energy scans all over the available frequencies range.

All the previous considerations give support to stablish cognitive capabilities to the final application. In addition to the requirements to be defined, they will define the model of the final cNGD implementation.

3.2. First Cognitive Device review

The FCD was developed in 2011 at the LSI by Fernando Lopez Lara[42] [6]. It suppossed the first hardware platform fully oriented to CWSN development. Integrating

[3] Very common in WSN. Devices remain asleep and wake up just on specified time-slots to execute their functions.

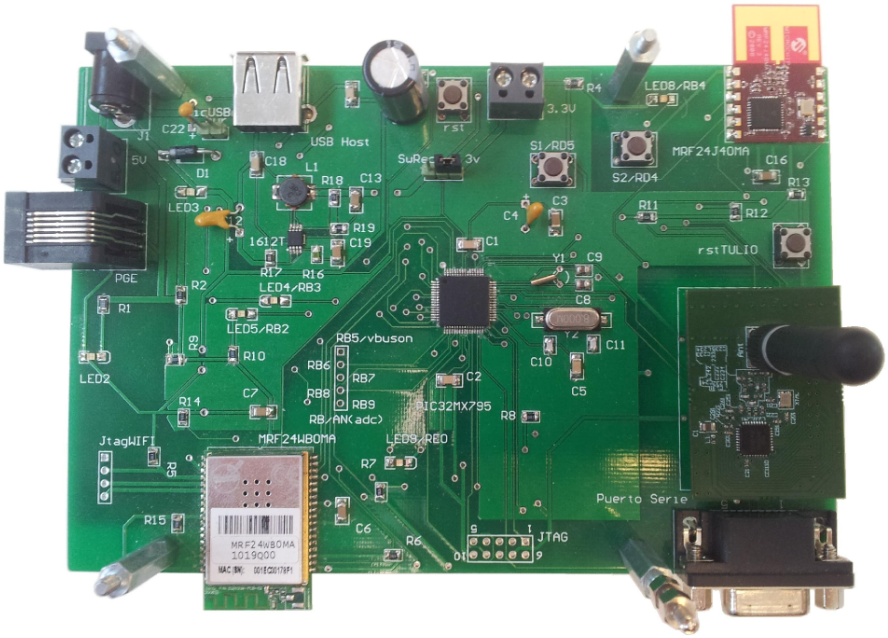


Figure 3.2: Picture of the FCD, developed at LSI in 2011

hardware and software, it gave the chance to develop and test algorithms, strategies and and applications for CWSN. Moreover, it allowed to analyse suitability for radio interfaces, computating capability. It gave the strengths and weaknesses to stablish the fundamentals on future designs.

While constituting the first device meeting its features and even being a very complete and close aproach to the CWSN concept, the FCD introduced several improvable issues and troubles found after its implementation and evaluation. Its power consumption, size and cost, together with other not achieved but desired requirement, make the device insuitable for CWSN testbedding purposes and claim for a new design.

The FCD has a Microchip PIC hosting a MIPS (*Microprocessor without Interlocked Pipeline Stages*) M4K, a 32-bits MCU (*Microcontroller*) unit developed by MIPS Technologies. It has a Hardvard architecture employing a five-stages pipeline and a RISC (*Reduced Instruction Set Computer*). The chosen model, a PIC32MX795F512H[43], integrates a 512 KB Flash Memory and a 128 KB general purpose SRAM (*Static Random Access Memory*). It allows a maximum 80 MHz clock frequency and it achieves a throughput as high as 1.65 DMIPS/MHz[4]. This PIC was found to offer too high features for our requirements, hence existing a reducible amount of power consumption on this module. Reducing capacity with regards to Flash and **RAM!** memory is seen as a positive option.

The FCD includes three radio interfaces enabling access to two different spectrum regions. Two of the selected interfaces work on the 2.4 GHz band and the third one over the 868 MHz, corresponding to the ISM bands in Spain. Over the 868 MHz band used to operate a Tulio^{TM}[44] transceiver oriented to **LOWPAN!** and IEEE 802.15.4 compatible. For the 2.4 GHz band, two Microchip modules were selected, a MRF24J40[45] mo-

[4] **DMIPS!** divided by **CPU!** frequency. Dhrystone is a synthetic computing benchmark program become representative of general processor performance.

dule using Microchip propietary protocols such us MiWi^{TM} P2P[46], MiWi^{TM} Mesh, MiWiPRO^{TM}[47] and a MRF24WB0MA[48] module IEEE 802.11 compatible as Wi-Fi. Firmware running on the FCD operated by using three different protocol stacks. Tulio^{TM} firmware was provided by AWD and the communications to the main controller take place through an UART. Stacks for MiWi[49] and TCP/IP[50] protocols are provided freely by Microchip, being the first one significantly lighter and simpler than the second one. Communications to these transceivers use SPI interfaces.

Figure 3.3: Architecture model of the FCD, developed at LSI in 2011

The Tulio^{TM} module offers a very low-consumption but it contains a Texas Instrumen microcontroller increasing complexity on the PIC to transceiver communications, moreover, this fact raise the global consumption up. Maintaining this interface will be disputed. On the other hand, the WiFi interface seems to be inappropiate for WSN due to its high power consumption and hibernation-related problems, besides its complex, resources-consumming communication stack. Even though this interface acts as a gateway, new options are highly needed. MRF24J40 gives a throughput suitable for the already described requirements, thus it could be a good candidate for the new design.

Regarding firmware options, the situation resulting from combining three different stacks becomes messy, confussing, power and resouces-consumming, not suitable to deal with an application layer and a cognitive layer properly. Hence, using the developed HAL[7] integrating three stacks and presenting a straightforward **API!** for upper layers better operation seems a good choice for this work.

The node comprises two USB terminals and a RS232 interface for debugging and interconnection purposes. Power supply system accepts 3.3 V and 5 V options including a voltage regulator and a charge pump.

Maintaining all these interfaces supposes larger device size and greater power consumption. A review about keeping all them as well as all the power supply options will be brought to pass, some of them seemed unuseful and innefficient.

Regarding other issues, reducing the general size, making the device more scalable or modular are indeed needed on the cNGD.

3.3. Hardware Abstraction Layer review

The work in [7] described an implemented new firmware for the cNGD. The firmware runs over PIC32 architectures. It was developed over the FCD but slightly adapting the hardware for a more complete development. The firmware offers access to three different regions over the radio spectrum by means of Microchip transceivers and a MiWi^{TM} protocol stack, appropriately modified and adapted to allow using more than one transceiver.

In order to abastract the application from the hardware and software complexity design, the firmware includes a straightforward HAL to deal easily with the **RI!**s within a close set of functions. In this way, node usability improves and applications cost and developing time decrease.

The new firmware suposses several advantages:

- Versatility and configurability are given. Hardware modifications and new modules are possible with minimal software adaptation.
- Firmware takes care of the protocol stack management, being the application just responsible for messages processing.
- MiWi^{TM} Protocol stack adaptation makes a better efficient use of resources and removes complexity.
- Devices fabrication costs are reduced since some modules are not needed anymore and less featured controllers are suitable.
- Sleeping modes provided by the firmware bring the key for autonomous operation modes. Whenever circumstances permit it, enabling sleeping modes will drop significantly the power consumption.

This software module must be taken into account at the design stage for its inclusion into the cNGD. It also might be needed of adaptation or debugging tasks due to its short life-time and usage.

3.4. Cognitive Radio Module review

3.5. System Requirements

Once described the CWSN node model and after evaluating the main related developments, it is time to define the requirements for our cNGD. Gathered, reserarchers at LSI specialiced on CWSN, dicussed and shared impressions about the requirements that the cNGD should meet. These were classified as follows:

- Essential requirements
    - Working operation, at least, over two ISM bands (868 MHz and 2.4 GHz). Having, as far as possible, fully-configurable transceivers.

- Modularity.
- IEEE 802.11 standard interoperation possibilities.
- External pluggable antenna possibilities.
- Development-oriented. Comprising debugging tools.
- Working under a single development framework.
- Useful and powered to try concepts referred to optimization strategies for:
  - Security.
  - Power consumption.Bajo consumo
  - Syncronization.
  - QoS.

- Desirable features
  - Portable and autonomous power supply options.
  - Remote application-loader.
  - Reduced size.
  - Working over three ISM bands (433 MHz, 868 MHz, 2.4 GHz).
  - Monocore-based arquitechture.
  - Battery charge-state monitoring.
  - Real radio headers switching possibilities so as to use a single transceiver for more than one frequency band.

Furthermore, it should responds to WSN normal requirements:

- *Scalability.* Given the pontentially large amount of nodes compossing a WSN, the model call for a easily scalable design.
- *Ubiquitous computing.*. Each node hosts some computing capacity, giving to the network the chance for distributed cognition. Thus, robustness and stability is given to the set.
- *Cost.* Due to the same previous reason, low-cost is a requirement. Otherwise their price makes networks non-commercially-viable.
- *Power comsumption.* It must be prepared to operate with battery and achieve a fairly long autonomy [5].
- *Throughput.* It must be slightly higher than usual. Regarding the generic nature of the platform it should be prepared for the widest possible range of applications. Cognition, on the other hand, increases as well the need for computation capabilities dealing with several interfaces and increasing the number of data transmissions.
- *Communication data-rate.* Not too high data-rate transmissions are usually needed. A few tens or hundreds of KB/s should work well.
- *Security.* Radio Interfaces allowing manageable security mecanisms. Being possible to deal with confidential or private data sufficiently safe.

[5] Common WSN applications autonomy last for years. The platform must emulate similar conditions.

3.6. Technology

Step by step, all the needed technologies for our design will be evaluated and compared to the employed by the FCD.

3.6.1. Microcontroller

Based on the requirements described in 3.5, it seemed necessary to keep the number of cores reduced to one unit. Futhermore, using a 32-bits Microchip PIC was an impossed design decision, as it was said.

The criteria to choose a microcontroller were:

- The less featured and simplest microcontroller that suits our operation memory parameters. FCD showed that a Flash memory above 200 KB was enough and a **RAM!** memory over 32 KB fits our needs. This helps to keep down the microcontroller power consumption. All 32-bits PICs family have a throughtput high enough.
- Some peripherals are essential to accomplish required tasks. At least three SPIs[6] would operate to communicate the microcontroller to the radio transceivers. Moreover, peripherals for debugging such as UARTs or USBs must be available simultaneously. Appart from that, it should contain other buses and peripherals accessibles for modularity. Probably a 100-pins microcontroller could satisfy the access to multiple peripherals better than smaller scales.
- Lowest price.

The different options included at Microchip catalog, described and showing their main features, are shown in table 3.1.

32-bits Microchip microcontrollers													
Microcontroller	Max. Frequency	Memory (kB)		Peripherals						ADC	Pins	Consumption	Euros
		Flash	RAM	SPI	UART	I2C	USB	CAN	ETH				
PIC32MX664F128H	80	128	32	3	6	4	Full Speed Host Dev. OTG	0	10/100 BaseT	16	64	bla bla bla bla	0
PIC32MX664F128L				4		5					100		
PIC32MX764F128H				3		4		1			64		
PIC32MX764F128L				4		5					100		
PIC32MX675F256H		256	64	3		4		0			64		
PIC32MX675F256L				4		5					100		
PIC32MX775F256H				3		4		2			64		
PIC32MX775F256L				4		5					100		
PIC32MX775F512H		512		3		4		2			64		
PIC32MX775F512L				4		5					100		
PIC32MX795F256H			128	3		4		2			64		
PIC32MX795F256L				4		5					100		

Table 3.1: Comparative table of 32-bits familly Microchip PICs.

3.6.2. Radio Interfaces

One of the desired requirements is enabling radio activity over three ISM bands (434 MHz, 868 MHz and 2.4 GHz), so in order to achieve it, compatible transceivers

[6] Most of commercial radio transceivers set their communication with the **CPU!** over SPIs

Microcontroller	Max. Frequency	Memory (kB)	Peripherals
col 1	col 2	col 3	

Table 3.2: Comparative table of 434 MHz transceivers modules.

on these bands must be studied. We first took two decisions based on the experience brought by the FCD.

The FCD access the 868 MHz band using a Tulio^{TM} module. This module brings global complexity to the design, it includes a core itself and the communication between cores are driven by the UART, the low data-rate communication provided does not seem to support our goals either. To keep the single-core architecture, lowering-down power consumption and meeting the requirements described, this module will be supressed and it will be looked for a replacement.

WiFi transceiver, MRF24WB0MA, embedded by the FCD raises up the power consumption to unsuitable levels in WSN. The stack to manage the hardware is very heavy computationally and memory-consuming compared other usual protocol stacks in WSN. Even being a requirement to stablish a gateway to the IEEE 802.11 standard, it cannot be included on the design of a general node. New ways to stablish the gateway will be studied, maybe through a pluggable expansion module. The low-consumption, low-resources and simple scheme looked in the cNGD cannot afford to include this transceiver.

IEEE 802.15.4[34] standard defines MAC and **PHY!** levels referred to the OSI model for low-consumption WPANs. It is a widely used standard on WSN and commonly employed protocols are 802.15.4 based-on or compatible.

wirelesscomparison

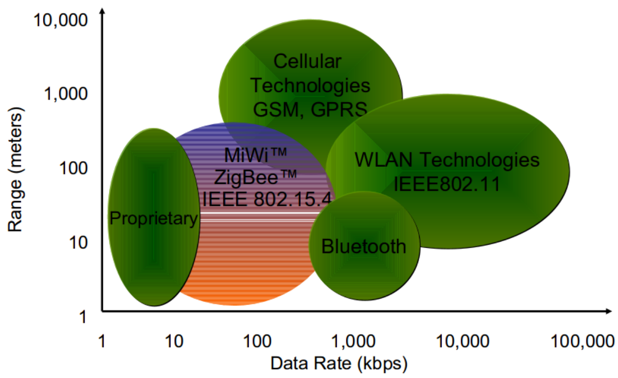


Figure 3.4: Main wireless networking options comparison

3.6.3. Serial Communication

Serial communication is a feature very important for applications development and debugging, it allows wiring the node and stablishing communication between the cNGD and any other device, normally a computer or storaging devices to track data. The usual paths to carry through these communication tasks are peripherals such as the UART, by attaching a simple circuit and RS232 connector, or more recent implementations enable communications through USB.

While the FCD includes two USB connectors, a microUSB and normal one, together with a RS232 communication module, three communcation ways to interface the node seems too many. These modules are size and power consuming.

microUSB connectors show a reduced size compared to first connectors and they do expand the first connectors capabilities. The idea include a normal connector gives some interconnection opportunities with attachable devices like mouses, keyboards, or portable memories in which the node addopts a *master* role facing a *slave* device. This feature supposses the inclusion of a power consumming circuitry to raise the voltage up to 5 V into the USB, giving some complexity to the design. In order to fit the requirements it does not seem to be needed this last capability on each node; a microUSB connector would be enough.

RS232 communication so does needs its own power supply. The size and cost for an RS232 connector and circuitry on each node is too high for a serial communication module, needing for a MAX3232 chip; even more, after comparing to a microUSB option. An optional module for RS232 might be a good option given its wide acceptance and utility in WSN despite the global use of USB.

3.6.4. Power Supply System

The power supply sytem designed for the FCD includes some modules susceptible to be supressed or replaced to keep the simplicity and reduce the comsumption.

The MCP1612[51] buck regulator specifications fit the supply requirements on excess so a less-featured device might be enough in the new design. The concrete parameter to reduce at the MCP1612 is the maximum output current, up to 1 A.

The MCP1253-33X[52] charge-pump, responsible for raising the voltage up to 5V to operate over USB as master, could be removed in the new design if finally this option is not implemented.

3.6.5. Timing

Timing options included on the FCD supose a low-consumption oscillator for real-timing and a second oscillator for maximum operation frequency. It does not appear any problem related to the timing configuration. The configuration defined fits the requirements and, firstly, seems a good option to keep it unchanged.

3.6.6. Application Capabilities

Application capabilites on board of FCD are poor. Appart from interacting with the **RI!** and serial communication, the board does not offer options for sensing/controlling applications neither other more complex possibilities such as including new communication modules. This is because the FCD does not embbed any expansion header or plug where adapting any new design to expand to new features.

The new design calls for expansion options where application capabilities could be widely and easily open attaching modules including the required design. A complete expansion header for WSN should include access to the following peripherals/buses:

- I^2C. Being the most common way to interconnect sensors to the controller.
- *USB*. For serial communication, mainly to a host device.

- *UART.* For asyncronous serial communication to devices.
- *SPI.* As a standard serial communication peripheral.
- *Ethernet.* For IEEE 802.11 compatiblity.
- *Interruptions.* Enabling interrupting the **CPU!** without employing polling.

3.7. Conclusions

After having a review all over the recent implementations, software and hardware, related to the CWSN that might bring some guidances in our design; after evaluating the used technology and analysing the weaknesses and detecting some problems; after defining some minimal requirements to fit and apply them to our evaluations, the obtained conclussions to face the design stage are these that follows:

- The model implemented by the FCD is quite close to the one pursued. It will serve as guide in our designing process since its review reveals significant technology and behavioral-related information.
- A new configuration regarding size and cost, facilitating a current very poor scalability.
- Some other software implementations such as the HAL will help us saving time on the software development and it proposses a very complete firmware that fits our requirements. It includes very useful features and, even if needed some slight adaptations, it must be compatible with our cNGD design.
- FCD includes a microcontroller too featured, implying higher power consumption and cost, for the set requirements. A new study seems needed.
- **RI!**s used by the FCD open communication on two frequency bands. They show a very inefficient working and high consumption behavior due to:
  - Coexistance of three eterogenous transceivers and different protocol stacks. Bringing complexity and operation inefficiency.
  - Presence of a WiFi transceiver, with consumptions up 160mA at TX.
  - A Tulio^{TM} transceiver whose inclusion, hosting a core by itself, suposses a multicore implementation.

  A reconfiguration of the **RI!**s is needed. Bringing homogeneity and a standard protocol for WSNs such as IEEE 802.15.4 to implement. Besides, desirable requirements call for a third frequency band to implement.
- Serial communication system claims for simplifications, the same as the power supply system.
- Application capabilities must be expanded to enhance modularity and node capabilities. Expansion pluggable options must be included to the main peripherals. Access to 802.11 standard is a requirement.
- A portable supply system must urgently be completely developed.

Chapter 4

Design Study

Surf it, scroll it, pause it, click it,
cross it, crack it, switch - update it
name it, rate it, tune it, print it,
scan it, send it, fax - rename it

Thomas & Guy-Manuel, Daft Punk

In this chapter the platform design is described. Design decisions, specifications, schemes and needed calculations will be exposed. Detailled characterstics of any chosen component, including microcontroller, radio interfaces, power-supply options will be provided.

4.1. Global Hardware Description

Attending to the already described requirements and the conclusions obtained from the FCD review, the following decisions have been taken before proceeding with the design process.

As part of the main goal, the firmware reviewed in section 3.3 will be used. It supposes an aproach to the requirements achievement since it gives support for three interfaces, it supposes a reduction on the computation load and therefore, on the needed resources and power consumption. Moreover it will facilitate the development, offering a stable firmware version to work over and avoiding software development tasks. This fact will force the design to keep one architecture compatible with the firmware, hence a 32-bit Microchip PIC is required as microcontroller.

Core unit is a PIC32675F256L, a midrange microcontroller from the mentioned family. Being the humblest of the options meeting memory performance and peripherals requirements. On the other hand, its 100 pins allow a better access of the peripherals provided.

The device can access three different frequency bands over the spectrum, fulfilling one of the desired requirements described in section 3.5. The chosen operation frecuencies will be 434 MHz, 868 MHz and 2.4 GHz. Coupling the ISM bands in most part of Europe. This bands are preferred for WSN due to the data-rate, transmission power and transmission range parameters they offer. This configuration places the device on the bound of complexity and cost. At the same time, this feature is essential for a CWSN proper investigation, giving radio communication opportunities not provided by any other similar device so far. Moreover, a full exploitation of the firwmware described in 3.3 can be done, since it offers an integrated MiWi^{TM} stack for three **RI!**.

The three **RI!** are based on the IEEE 802.15.4 standard for WPANs, commonly used in WSN. Specifically, the set of interfaces will operate under MiWi^{TM} or MiWi^{TM}P2P protocol. They both are proprietary protocols designed by Microchip Technology that uses small, low-power digital radios. It is open source option designed for low data transmission rates (up to 250Kbit/s) and short distance (up to 100 without obstacles), cost constrained networks. Main difference between MiWi^{TM} and ZigBee^{TM} is complexity. MiWi^{TM} offers a much more simple operation, resulting in a lighter implementation. The size required for the MiWi^{TM} stack is 3-10 KB on the ROM depending on the node role while ZigBee^{TM} takes 20-40 KB. MiWi^{TM} is free of cost and it does not require for licenses adquisition as long as Microchip components are used, in fact Microchip requires the use of MiWi^{TM} for its products.

Since there were not compatible and suitable size commercial options for 868 MHz and 434 MHZ **RI!**s, a custom full implementation of these interfaces was required. These **RI!** are based on the MRF49XA Microchip transceiver, whereas option at 2.4 GHz is a MRF**.

Power supply will be able to take place through three ways, a μUSB, a block terminal and a DC terminal. Two first options will take a 5V supply, whereas the third one will take 3.3V. This last option is thought to be supplied by a battery. μUSB option serves as serial communication chance, and since USB provides 5V power supply, this is employed. A second 5V supplying connector opens possibilites to not compulsory useUSB. A software-driven power supply system to the **RI!**s allows the application to switch the power supply to these modules.

The device offers serial communication through the already named μUSB options. Moreover, it gives access to to different peripherals through a pair of 20-pin headers. The list of approachable peripherals and pins covers battery connection (for charging purposes), **GPIO!**s, **MCLR!** pin, external interruptions, analogue inputs, USB, Ethernet module, I2C bus, UARTs and SPI. These option gives flexibility, modularity and versatility to the device. It provides possibilities for multiple kind of applications and open the design to new implementations and extensions for a particular aplications.

For this work it was designed a simple serial communication complement that links one UART and a classic rs232 interface over the so-called rs232SHIELD. This interface would facilitate the software development since the firmware just allowed debugging through the UART at first. A battery charger Ni-Mh and Ni-Cd was also designed and implemented as a utility for portability options. The device was called as chargerSHIELD.

4.2. Altium Designer

For the whole designing task, a **EDA!**[1] software will be use. Altium Designer, being one of the most important **EDA!** softwares, is commonly used by researchers at LSI. All the cNGD design process is carried through Altium Designer on its version v.13********************* MIRAR.

[1]Electronic design automation is a category of software tools for designing electronic systems such as printed circuit boards and integrated circuits.

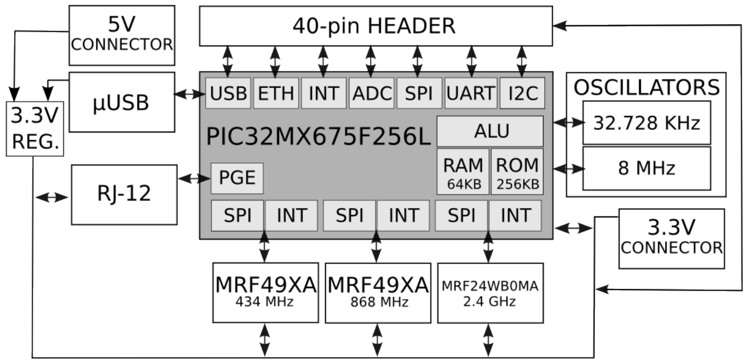


Figure 4.1: Architecture Model of the cNGD

Altium Designer is software package for printed circuit board, **FPGA!** and embedded software design, and associated library and release management automation. It is developed and marketed by Altium Limited of Australia.

Despite the amount of functionalities offered by Altium Designer the two main options needed for this project are schematic capture, for circuit edition, and **PCB!** design, for subsequent layout deployment.

Options provided by the schematic capture module, required for the design task, includes:

- Component library management.
- **SPICE!** mixed-signal circuit simulation.
- Netlist export.
- Reporting and BoM facilities.
- Multi-channel, hierarchical schematics and design re-use.

On the other hand, required option from the **PCB!** design module are:

- Component footprint library management.
- Component placement.
- Manual trace routing, with support for multi-trace routing.
- Interactive 3D editing of the board and MCAD export to STEP
- Manufacturing files generation with support for Gerber formats

4.2.1. agus lib

For the accomplish the full design of the platform over Altium Designer, a component library with all the requried but not found models was set all along the design proccess.

As said, the library includes models from all those components needed but not found as well as modifications of existing models in order tu suit the design criteria. Every contained model embbeds schematic, footprint and 3D model. 3D models are useful for 3D rendering and proper hardware fitting checkings purposes.

ANEXAR ¿libreria? ***

4.3. Main Board - cognitiveNextGenerationDevice

4.3.1. Description

4.3.2. Schematics

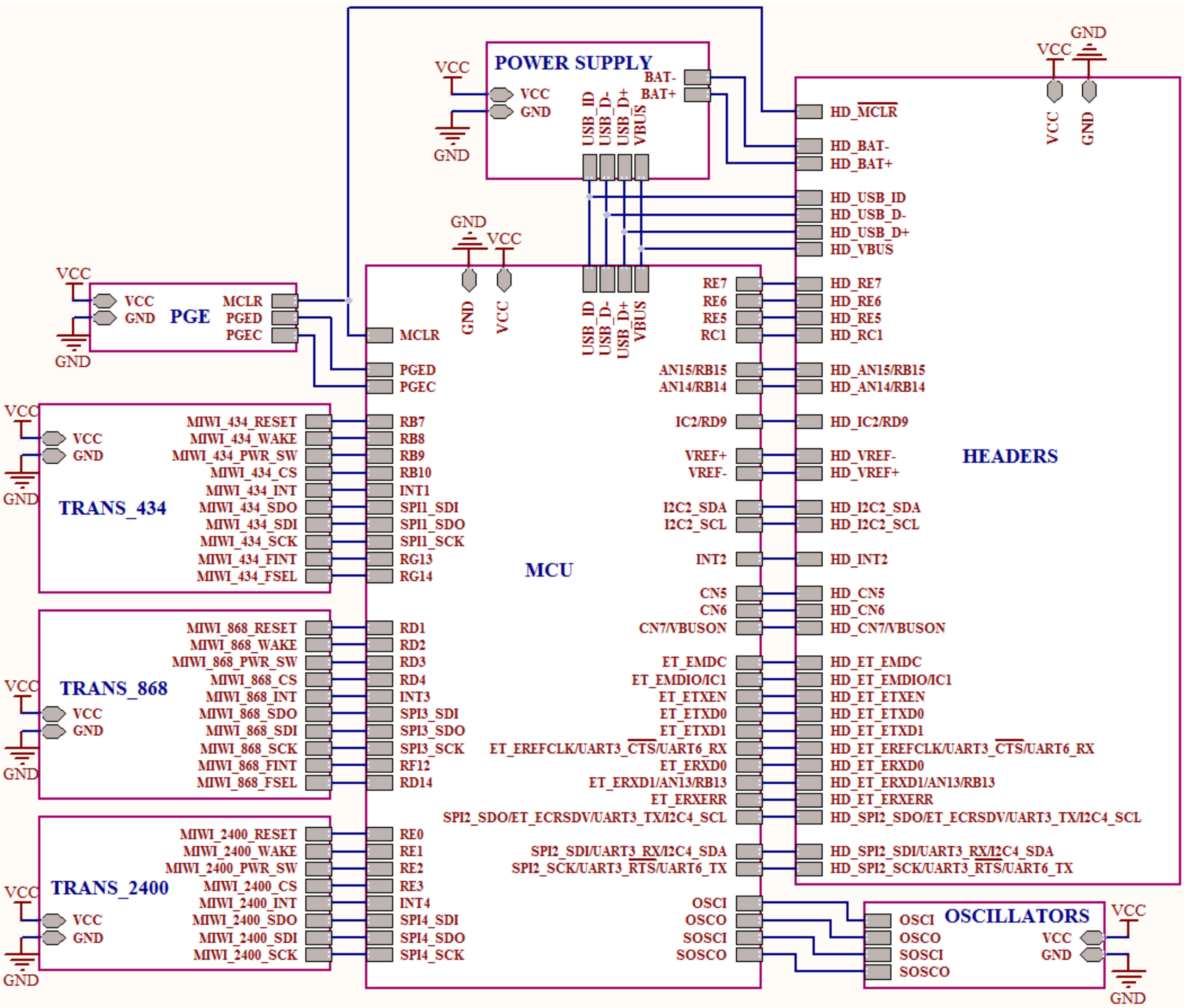


Figure 4.2: cNGD general schematic

4.3.3. Power Supply System

4.3.3.1. Battery

4.3.4. Microcontroller

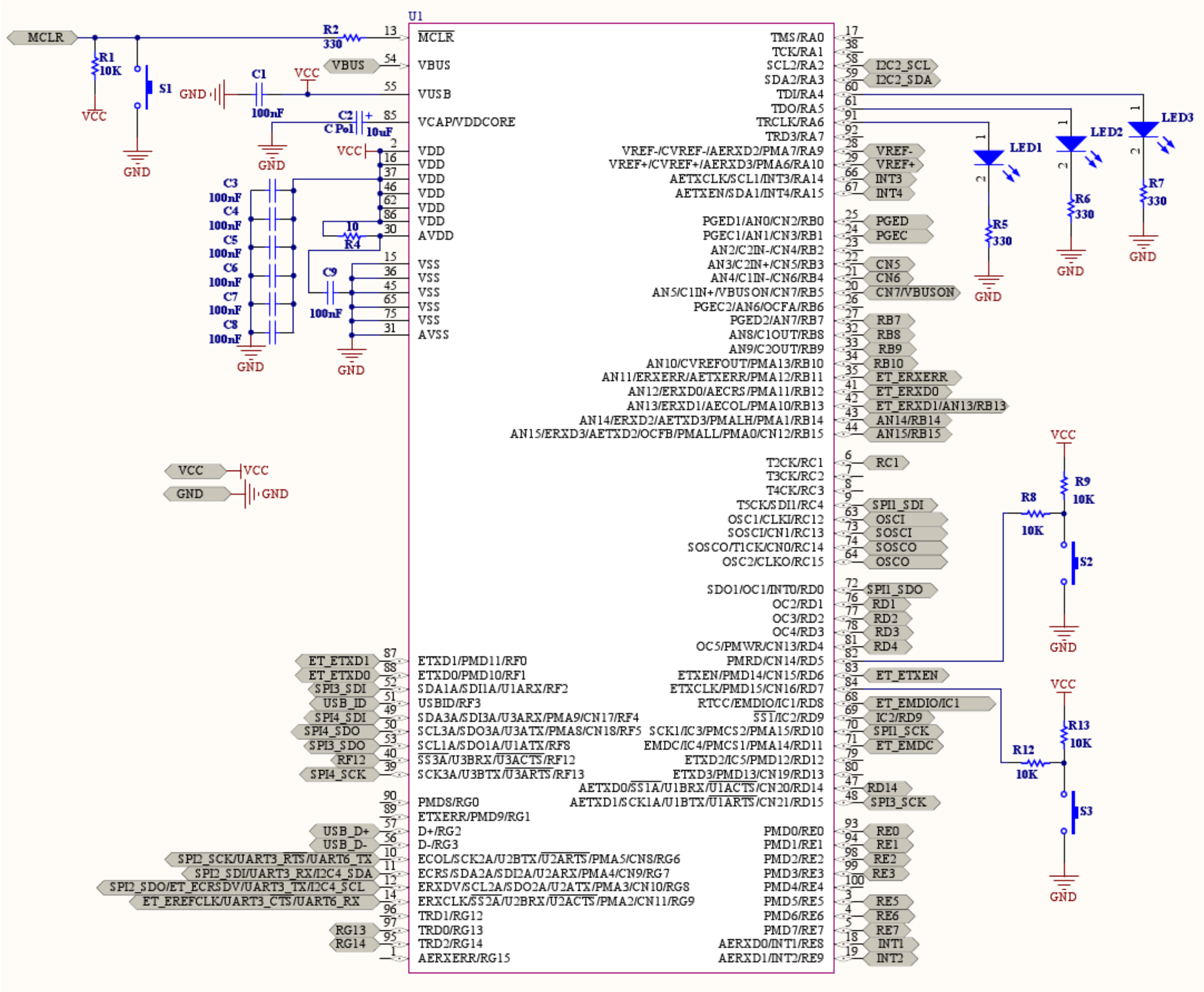


Figure 4.3: Microcontroller specific schematic

4.3.4.1. Pinout

4.3.5. Radio Interfaces

The MiWi P2P protocol stack supports star and peer-to-peer wireless-network topologies, useful for simple, short-range, wireless node-to-node communication. Additionally, the stack provides sleeping-node, active-scan and energy-detect features while supporting the low-power requirements of battery-operated devices.

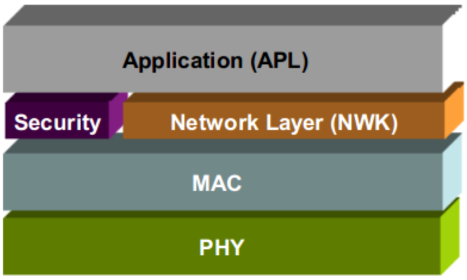


Figure 4.4: MiWi^{TM} Protocol stack.

4.3.5.1. Software Controlled Power Supply

4.3.6. Timing

4.3.7. Expansion Headers

4.3.7.1. Pinout

4.3.7.2. Considerations

4.4. Transceivers - μTrans 434/868

4.4.1. Description

4.4.2. Schematics

4.5. Serial Communication Board - rs232SHIELD

4.5.1. Description

4.5.2. Schematics

4.6. Transceivers - chargerSHIELD

4.6.1. Description

4.6.2. Schematics

4.6.3. Simulation

Chapter 5

Implementation Study

Time of your life

Resumen

5.1. Main Board - cognitiveNextGenerationDevice

5.1.1. Layout

5.1.2. Mounting

5.1.3. Testing

5.2. Transceivers - μTrans 434/868

5.2.1. Layout

5.2.2. Mounting

5.2.3. Testing

5.3. Serial Communication Board - rs232SHIELD

5.3.1. Layout

5.3.2. Mounting

5.3.3. Testing

5.4. Transceivers - chargerSHIELD

5.4.1. Layout

5.4.2. Mounting

5.4.3. Testing

5.5. Conclusions

Chapter 6

Software

Too long, can you feel it?
Too long, oh can you feel it ?

Resumen

6.1. Hardware Abstraction Layer

6.2. Cognitive Module

6.3. Application Layer

6.3.1. Conscumption Application

6.3.2. Security Application

6.4. Test Benches

Chapter 7

Testings and Results

At last the long wait is over
The weight is off my shoulders
I'm taking all control, yeah

7.1. Test Model

7.2. Consumption Application Test

7.3. Security Application Test

7.4. Test 1

Chapter 8

Conclusions

Frase

Fuente

8.1. Further Studies

test bed

crear funciones en hal para perifericos en headers

trabajar con transceptores a fin de crear un unico transceptor con 2 bandas e incluso añadir posibilidad de wake-on radio.

desarrollar shields de funcionalidades utiles tales como un acceso ethernet, 3g, gsm, otra de proposito general con puntos de soldadura,

cambiar el conector programador PGE por una versión simplificada mas barata y que ocupe menos espacio, incluso a traves de los headers. Ademas seria imprescindible de cara a un testbed el desarrollo de un sistema programador sin cablear.

cambio de arquitectura ->cambio de firmware

desarrollar firmware y protocolo desde 0

Over the air programming (OTAP)

wireless traces

Chapter 9

Legal Conditions

Television rules the nation

9.1. General Conditions

9.2. Particular Conditions

Chapter 10

Estimated Costs

Human, human, human, human,
Human, human, human, human,
Human, human, human, human,
Human, human, human after all

References

She's up all night to the sun
I'm up all night to get some
She's up all night for good fun
I'm up all night to get lucky

[1] Perera, C.; Zaslavsky, A.; Christen, P.; Georgakopoulos, D., "Context aware computing for the internet of things: A survey," *Communications Surveys & Tutorials, IEEE*, vol. PP, no. 99, pp. 1–4.

[2] Howitt, I.; Gutierrez, J.A., "IEEE 802.15.4 low rate - wireless personal area network coexistence issues," *Wireless Communications and Networking, WCNC 2003*, vol. 3, pp. 1481–1486, mar 2003.

[3] Mitola, J. III; Maguire, G.Q. Jr, "Cognitive radio: making software radios more personal," *Personal Communications*, vol. 6, pp. 13–18, Aug. 1999.

[4] Mitola, J. III, *Cognitive Radio An Integrated Agent Architecture for Software Defined Radio, PhD. Dissertation.* Royal Institute of Technology, Kista, Sweden, 2000.

[5] Akan, O.B.; Karli, O.; Ergul, O., "Cognitive radio sensor networks," *Network, IEEE*, vol. 23, pp. 34 – 40, jul 2009.

[6] López, F.; Romero, E.; Blesa, J.; Villanueva, D.; Araujo, A., "Cognitive wireless sensor network device for aal scenarios," *Lecture Notes in Computer Science*, vol. 6693, pp. 116–121, 2011.

[7] Domingo, J., *Diseño, optimización y prueba un nodo para una red de sensores inalámbrica con capacidades cognitivas, PFC*. Laboratorio de Sistemas Integrados, ETSIT-UPM, feb 2013.

[8] Rabaey, J.; Wolisz, A.; Ozer Ercan, A.; Araujo, A.; Burghardt, F.; Mustafa, S.; Parsa,A.; Pol "Connectivity brokerage - enabling seamless cooperation in wireless networks. technical report, berkeley wireless research center," sep 2010.

[9] R. W. Brodersen; A. Wolisz; D. Cabric; S. M. Mishra; D. Willkomm, "Corvus: A cognitive radio approach for usage of virtual unlincesed White Paper,,"

[10] Federal Communications Commission, "Spectrum policy task force," *Rep. ET Docket*, vol. 02.

[11] S. J. Kim, "Dynamic spectrum allocation with variable bandwidth for cognitive radio systems," *Communications and Information Technology*, pp. 106 – 109, sept 2009.

[12] Federal Communications Commission, "Facilitating opportunities for flexible, efficient, and reliablespectrum use employing cognitive radio technologies,notice of proposed rulemaking and order, fcc 03-322," dec 2003.

[13] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas of Communications*, vol. 23.

[14] Ian F. Akyildiz; W.-Y. Lee; M. C. Vuran; S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks (Elsevier) Journal*, sep 2006.

[15] R. Venkatesha; J.A. Hoffmeyer; H.S. Berger, "Cognitive functionality in next generation wireless networks," *IEEE Communications Magazine*, pp. 72 – 78, apr 2008.

[16] Z. Li; F.R. Yu; M. Huang, "A distributed consensus-based cooperative spectrum sensing in cognitive radios," *IEEE Trans. Vehicular Technology*, vol. 59, pp. 383 – 393, jan 2010.

[17] Foukalas, F.T.; Mathiopoulos, P.T.; Karetsos, G.T., "Joint optimal power allocation and sensing threshold selection for su's capacity maximisation in ss crns," *Electronics Letters*, vol. 46, pp. 1406 – 1407, sep 2010.

[18] Stevenson, C.; Chouinard, G.; Zhongding Lei; Wendong Hu; Shellhammer, S.J.; Caldwell, W., "Ieee 802.22: The first cognitive radio wireless regional area network standard," *Communications Magazine, IEEE*, vol. 47, pp. 130 – 138, jan 2009.

[19] Alexiou, A. ; Haardt, M., "Smart antenna technologies for future wireless systems: Trends and challenges," *IEEE Communications Magazine*, vol. 42, no. 9, pp. 90 – 97, 2004.

[20] Berezdivin, R.; Breinig, R.; Topp, R., "Next-generation wireless communications concepts and technologies," *IEEE Communications Magazine*.

[21] Schwartz, B.; Jackson, A.W.; Strayer, W.T.; Zhou, W.; Rockwell, R.D.; Partridge, C.;, "Smart packets for active networks," *OPENARCH 9́9*, pp. 90 – 97, 1999.

[22] Gelenbe, E.; Lent, R.; Xu, Z., "Design and performance of cognitive packet networks," *Performance Evaluation*, vol. 46, no. 2 - 3, pp. 155 – 176, 2001.

[23] P. Mähönen, J. Riihijärvi, M. Petrova, and Z. Shelby, "Hop-by-hop toward future mobile broadband ip," *IEEE Communications Magazine*, vol. 42, no. 3, pp. 138 – 146, 2004.

[24] Ramming, C., "Cognitive networks," *DARPATech*, 2004.

[25] Saracco, R., "Forecasting the future of information technology: How to make research investment more cost-effective," *IEEE Communications Magazine*, vol. 41, pp. 38 – 45, dec 2003.

[26] Neel, J.O.; Reed, J.H.; Gilles, R.P., "Convergence of cognitive radio networks," *Proc. of IEEE WCNC 2004*.

[27] Neel, J.O.; Buehrer, R.M; Reed, J.H.; Gilles, R.P., "Game-theoretic analysis of a network of cognitive radios," *Proc. of the Midwest Symposium on Circuits and Systems*, vol. 3, pp. 409 – 412, 2002.

[28] Ganesan, G.; Li, Y., "Cooperative spectrum sensing in cognitive radio networks," *Proc. of IEEE DySPAN*, 2005.

[29] Mishra, S.M.; Sahai, A.; Brodersen, R.W., "Cooperative sensing among cognitive radios," *Proc. of IEEE ICC 2006*.

[30] Pawelczak, P.; Prasad, R.V.; Xia, L.; Niemegeers, I.G.M.M, "Cognitive radio emergency networks - requirements and design," *Proc. of IEEE DySPAN 2005*, pp. 601 – 606, 2005.

[31] Raychaudhuri, D.; Mandayam, N.B; Evans, J.B.; Ewy, B.J.; Seshan, S.; Steenkiste, P., "Cognet: An architectural foundation for experimental cognitive radio networks within the future internet," *Proc. ACM/IEEE MobiArch'06*, pp. 11 – 16, dec 2006.

[32] Thomas, R.W., *Cognitive Networks, PhD. Dissertation.* Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, jun 2007.

[33] L. A. D. R. W. Thomas, D. H. Friend and A. B. MacKenzie, "Cognitive networks: Adaptation and learning to achieve end-to-end performance objectives," *IEEE Communications Magazine*, vol. 44, pp. 51 – 57, dec 2006.

[34] IEEE, "IEEE 802.15. WPAN^{TM} task group 4,"

[35] Machado, R.; Tekinay, S., "A survey of game-theoretic approaches in wireless sensor networks," *Computer Network*, vol. 52, pp. 3047 – 3061, Nov 2008.

[36] Reznik, L.; Von Pless, G., "Neural networks for cognitive sensor networks," *Proc. IEEE Int. Joint Conf. Neural Network., IJCNN 2008*, pp. 1235 – 1241, Jun 2008.

[37] Akan, O.B.; Karli, O.; Ergul, O., "Cognitive radio sensor networks," *IEEE Network*, vol. 23, pp. 34 – 40, Jul 2009.

[38] Cavalcanti, D.; Das, S.; Wang, J.; Challapali, K., "Cognitive radio based wireless sensor networks," *Proc. 17th Int. Conf. Comput. Commun. Networks, ICCCN*, pp. 1 – 6, 2008.

[39] Vijay, G.; Bdira, E.B.A.; Mohamed Ibnkahla, M., "Cognition in wireless sensor networks: A perspective," *IEEE Sensors Journal*, vol. 11, mar 2011.

[40] Tennenholtz, M., "Game theory and artificial intelligence," *Foundations and Applications of Multi-Agent Systems. Berlin, Germany: Springer-Verlag*, vol. 2, no. 4, p. 51, 2002.

[41] I. F. Akyldiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Network J.*, vol. 50, pp. 2127 – 2159, Sep 2006.

[42] López, F., *Diseño e implementación de un nodo para redes de sensores con capacidades cognitivas, PFC.* Laboratorio de Sistemas Integrados, ETSIT-UPM, dic 2001.

[43] Microchip Technology Inc., *PIC32MX5XX/6XX/7XX Family Data Sheet.*

[44] Advanced Wireless Dynamics, *Tulio^{TM} Datasheet.* 2011.

[45] Microchip Technology Inc., *MRF24J40MA Data Sheet 2.4 GHz, IEEE Std. 802.15.4^{TM} RF Transceiver Module.*

[46] Microchip Technology Inc., *AN1204 Microchip MiWi^{TM} P2P Wireless Protocol.*

[47] Microchip Technology Inc., *AN1371 Microchip MiWi^{TM} PRO Wireless Networking Protocol.*

[48] Microchip Technology Inc., *Microchip MRF24WB0MA/MRF24WB0MB Data Sheet 2.4 GHz, IEEE Std. 802.11b^{TM} RF Transceiver Module.*

[49] Microchip Technology Inc., *AN1066 Microchip MiWi^{TM} Wireless Networking Protocol Stack.*

[50] Microchip Technology Inc., *AN833 The Microchip TCP/IP Stack.*

[51] Microchip Technology Inc., *MCP1612 Single 1A, 1.4 MHz Synchronous Buck Regulator.*

[52] Microchip Technology Inc., *MCP1252/3 Low Noise, Positive-Regulated Charge Pump.*

List of Acronyms

AWD . . . . *Advanced Wireless Dynamics*

CN . . . . *Cognitive Network*

cNGD . . . . *Cognitive Next Generation Device*

CR . . . . *Corgnitive Radio*

CRmodule . . . *Cognitive Radio Module*

CWSN . . . . *Cognitive Wireless Sensor Network*

DIE . . . . *Departamento de Ingeniería Electrónica*

DSA . . . . *Dinamic Spectrum Access*

ETSIT . . . . *Escuela Técnica Superior de Ingenieros en Telecomunicación*

FCC . . . . *Federal Communications Commission*

FCD . . . . *First Cognitive Device*

HAL . . . . *Hardware Abstraction Layer*

I^2C . . . . *Inter-Integrated Circuit*

ISM . . . . *Industrial, Scientific and Medical*

LSI . . . . *Laboratorio de Sistemas Integrados*

MAC . . . . *Medium Access Control*

MCU . . . . *Microcontroller*

MIPS . . . . *Microprocessor without Interlocked Pipeline Stages*

Ofcom . . . . *Office of Communications*

OSI . . . . *Open Systems Interconnection*

PIC . . . . *Peripheral Interface Controller*

QoS . . . . *Quality of Service*

RISC . . . . *Reduced Instruction Set Computer*

RSSI . . . . *Received Signal Strength Indication*

SDR .... *Software-Defined Radio*

SN .... *Sensor Network*

SPI .... *Serial Peripheral Interface*

SRAM .... *Static Random Access Memory*

UART .... *Universal Asynchronous Receiver-Transmitter*

UPM.......... *Universidad Politécnica de Madrid*

USB .... *Universal Serial Bus*

WN .... *Wireless Network*

WPAN........ *Wireless Personal Area Network*

WSN.......... *Wireless Sensor Network*