UNIVERSITA' DEGLI STUDI DI ROMA
"LA SAPIENZA"

Tesi di Laurea Specialistica in
Ingegneria delle Telecomunicazioni

"CLUSTERING OF COGNITIVE RADIO NODES BASED ON HYBRID ENERGY AWARE SPECTRUM SENSING"

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Anno Accademico 2007-2008

Grazie

Grazie alla prof. Di Benedetto per questa esperienza di lavoro concessami la quale mi ha dato modo di crescere ed arricchirmi in un ambiente veramente piacevole come quello del laboratorio ACTS.

Grazie a Luca e al Dome per tutto il supporto che mi hanno dato sempre con molta generosità, per tutte le risate fatte durante le infinite ore giornaliere, soprattutto per essersi dimostrati bravissimi assistenti ed amici.

Grazie alla mia famiglia che ha creduto in me e nelle mie capacità aiutandomi nell'intraprendere il lungo cammino che mi ha portato fin qua.

Grazie a tutti gli amici e le persone che mi sono state vicine in questi anni e con le quali ho condiviso questo periodo universitario.

Grazie a te Francesca, grazie mille per tutto quello che hai portato nella mia vita, per il modo in cui hai saputo essermi vicina, il regalo più bello che avessi mai potuto chiedere.

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Chapter 1

Introduction

1.1 Cognitive Radio and Cognition Concept

The world of wireless communication has seen in these last years a continuos growth of wireless services request. On the other hand radio resource is rarely used efficiently due to wrong or obsolete allocation policies, rigid regulation constraints, lack off flexibility and technological limitations.
Since Joseph Mitola coined the term *Cognitive Radio* (CR) [1], many researches have been devoted to develope new technologies to promote the *Spectrum Sharing* level in the apparent spectrum scarcity situation.

> *"A **Cognitive Radio** is a radio frequency transmitter/receiver that is designed to intelligently detect wheter a particular segment of the radio spectrum is currently in use, and to jump into (and out of, if necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmission of other authorized users."*

Mitola's intention with Cognitive Radio was to set the basis for the development of extremely intelligent wireless devices, able to smartly exploit the radio resource, but also to adapt their behavior to the specific needs of the single user while acting in compliance with the Regulation Authorities.
The Ideal Cognitive Radio device theorized by Mitola would be able to learn from the user and from past experiences and to always provide the highest possible information quality on a user/context basis. Such device embodies what is indicated as Full Cognitive Radio, a wireless agent equipped with Cognition.
The term *Cognition* is historically related to the human being, in particular to his capacity to organize thoughts, produce an intelligent behavior, solve problems and understand propositions.
A Full Cognitive Radio device must be endowed with rapid reconfigurability, signal processing capabilities and high computing performance for information processing. These features can be provided by an extremely efficient Software Defined Radio (SDR) embedded in the device [2], but costs and realization problems may arise; however Cognitive Radio can be seen as a sequence of intermediate steps (not Full CR decices), eventually towards Full Cognition, to make Cognitive Radio appealing to the Markets and acceptable to Regulatory Bodies.

A Cognitive Radio behaves according to five main actions:

1. OBSERVE: CR are aware of their surrounding environment.
2. PLAN: CR evaluate among several strategies.
3. DECIDE: CR are always capable to select one strategy of operation.

4. LEARN: CR can enrich experience by forming new strategies.
5. ACT: CR perform communication according to the selected strategy.

While Ideal CR devices process an extremely wide range of information, including audio-visual inputs and apply a dedicated language to learn and adapt heterogeneus parameters to the particular user needs, this work is mainly focused on the so-called ***Spectrum Sensing Cognitive Radio***, that considers the radio frequency spectrum as the only significant source of stimuli and information to be processed in a cognitive way.
Spectrum Sensing Cognitive Radio results particularly attractive in all those scenarios where devices must cope with interference, and in particular when different wireless networks must share the same radio resource and therefore interfere with one other during operation. In such contexts the major advantages potentially offered by a cognitive approach are represented by *coexistence capability* and even *Cooperation* among different networks or among nodes of one of the network in the heterogeneous radio environment.
One of issues in the CR framework remains undoubtedly the way the sensing phase is implemented. Sensing is crucial to radio cognition, since it represents the source of information to be processed and the basis for strategy planning and operative decisions.

Cooperation between groups of cognitive nodes (forming a cognitive network) can improve the sensing procedure and simplify the hardware complexity of the single CR device.

Cooperative Spectrum Sensing will be the key concept of all this work.

1.2 Background and Motivation

Nowadays it is plain the lack of available spectrum at frequencies that can be economically used for wireless communications. The Federal Communications Commission's (FCC) has pointed out an intense competition for use of spectra, especially at frequencies below 3 GHz, that leads to overlapping allocations. On the other hand, a series of studies of the FCC's Spectral Policy Task Force [3], have indicated a low utilization of the same bands with vast temporal and geographic variations in the usage of allocated spectrum. The real utilization of licensed frequencies ranges from 15% to 85% generating the so called *"White Spaces"*.
In 2003 the FCC advanced in a document [4] the usage of Cognitive Radio technology as an opportunity to implement negotiated or opportunistic spectrum sharing:

> *"advances in technology are creating the potential for radio system to use spectrum more intensively and more efficiently than in the past.*
>
> *Cognitive Radio technologies have the potential to provide a number of benefits that would result in increased access to spectrum and also make new and improved communication services available to the public."*

The FCC doesn't consider Full CR devices, but aware and adaptive radios with no learning capabilities, providing therefore its own definition of Cognitive Radio.
The European Commission too has recently officially issued the need for a new radio spectrum policy:

> *"a flexible, non-restrictive approach to the use of radio resources for electronic communications services, which allows the spectrum user to choose services and technology, should from now on be the rule, as opposed to the restrictive approach which is often still used today.*
>
> *Avoiding interference remains a key element of spectrum management, but the way it can be achieved has evolved due to technological progress. This progress means that the traditional spectrum management approach should be replaced by a more flexible one, which not only facilitates technical efficiency, but also economic efficiency in spectrum use."*

In the 2003 document FCC identifies four possible scenarios for Cognitive Radios. This work focuses its attention on the last scenario: *Non-voluntary third part access* where Unlicensed Cognitive devices operate at times and locations where licensed spectrum is not in use. Referring to this scenario we will call a licensed and an unlicensed networks *Pimary* and *Secondary* networks respectively.
Some systems in unlicensed frequency bands have achieved great spectrum efficiency, but are faced with increasing interference that limits network capacity and scalability.
A *Cognitive Secondary network* instead shares with the Primary network its licensed band. It exploits its technology to prevent interference towards Primary nodes and to create time and location dependent transmission opportunities for Secondary nodes.
A Secondary network creates a *virtual unlicensed band* within the Primary licensed band and should operate in the best trasparent way

towards a Primary network since it has no rights to any pre-assigned frequencies.
Spectrum sensing is best addressed as a cross-layer design problem. Cognitive Radio performances can be improved working on radio RF front-end sensitivity, signal processing techniques for Primary signal (chapter 2) and overall *Network Cooperation*, where users share their spectrum sensing measurements, which is the focal point of this work.

1.3 Organization of the work

Chapter 2 defines Spectrum Sensing function and its practical limitations.
Chapter 3 introduces the different tecniques of Cooperation in Cognitive Radio.
Chapter 4 describe the receiver implemented on this work.
Chapter 5 is devoted to the introduction of a novel *Cooperative Spectrum Sensing* model.
Chapter 6 discusses the performances the model.
Chapter 7 is dedicated to conclusions.

Chapter 2

Spectrum Sensing

2.1 Signal Processing Technique for Spectrum Sensing

Cognitive Radios are considered lower priority or Secondary users of spectrum allocated to a Primary user, so a fundamental requirement is to avoid interference to potential Primary users in their vicinity. On the other hand, Primary user networks have no requirement to change their infrastructure for spectrum sharing with Cognitive Networks. Therefore, Cognitive Radios should be able to independently detect Primary user presence through continuous spectrum sensing.
Different classes of Primary users would require different sensitivity and rate of sensing for the detection. For example, TV broadcast signals are much easier to detect than GPS signals, since the TV receivers' sensitivity is tens of dBs worse than GPS receiver.
In general, Cognitive Radio sensitivity should outperform Primary user receiver in order to prevent what is essentially a *hidden terminal problem*. This is the key issue that makes spectrum sensing very challenging research problem.
Under this condition, different signal processing techniques that are used in traditional systems have been valued [5], each one with its

advantages and disadvantages: *matched filter*, *energy detector* and *cyclostationary feature detector*.

2.1.1 Matched Filter

The optimal way for any signal detection is a *matched filter*.
It is a linear filter which maximizes the received signal-to-noise ratio in the presence of additive stochastic noise.
However, a matched filter effectively requires demodulation of a Primary user signal. This means that cognitive radio has *a priori* knowledge of primary user signal $X[n]$, such as modulation scheme, pulse shaping, packet format. Such information must be pre-stored in CR memory, but the inconvenience part is that for demodulation it has to achieve coherency with primary user signal by performing timing and carrier syncronization, even channel equalization. This is still possible since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection, for examples: TV signal has narrowband pilot for audio and video carriers, CDMA systems have dedicated spreading codes for pilot and synchronization channels, OFDM packets have preambles for packet acquisition.
In the standard detection problem, given the observed received signal $Y[n]$, the detector has to decide beetween two Hypotesis:

H_0 : Primary user is absent
H_1 : Primary user is present

If $X[n]$ is completely known to the receiver then the optimal detector is:

$$T(Y) = \sum_{n=0}^{N-1} Y[n]X[n] \gtrless_{H_0}^{H_1} \gamma, \tag{2.1}$$

here γ is the detection threshold.

The main advantage of *matched filter* is that due to coherency it requires less time to achieve high processing gain since only $N = O(1/SNR)$ samples are needed to meet a given probability of detection. However, a significant drawback of a matched filter is that a cognitive radio would need a dedicated receiver fo every primary user class.

2.1.2 Energy Detection

One approach to simplify matched filter approach is to perform non-coherent detection through *energy detection*.
It is a sub-optimal detection technique and it has been proved to be appropriate to use it to determine the presence of a signal in the absence of much knoledge concerning the signal. In order to measure the energy of the received signal the output signal of bandpass filter with bandwidth W is squared and integrated over the observation interval T. Finally the output of the integrator is compared with a threshold to detect whether the primary or licensed user is present or not. However, due to non coherent processing $N = O(1/SNR^2)$ samples are required to meet a probability of detection constraint.
In this case we have:

$$T(Y) = \sum_{n=0}^{N-1} Y^2[n] \gtrless_{H_0}^{H_1} \gamma, \tag{2.2}$$

Next picture shows the structure of an energy detector.
There are several drawbacks in using *energy detection*. First, a threshold used for primary user detection is highly susceptible to unknown

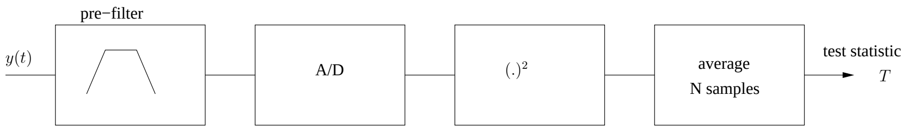

Figure 2.1 Block diagram of an energy detector.

or changing noise levels. Even if the threshold would be set adaptivily, presence of any in-band interference would confuse the energy detector. Furthermore, in frequency selective fading it is not clear how to set the threshold with respect to channel notches. Second, since the *energy detection* is only concerned with the energy of the incoming signal, it does not differentiate between modulated signals, noise and interference. Since, it cannot recognize the interference, it cannot benefit from adaptive signal processing for cancelling the interferer. Furthermore, spectrum policy for using the band is constrained only to primary users, so a cognitive user should treat noise and other secondary users differently. Lastly, an *energy detection* does not work for spread spectrum signals: direct sequence and frequency hopping signals, for which more sophisticated signal processing algorithms need to be devised.
However *energy detector* performs non-coherent detection, a technique that has been estensively used in Spectrum Sensing problems and will be analized more estensively later as model for the PHY layer used in simulations of networks in this work about Cooperative Spectrum Sensing.

2.1.3 Cyclostationary Feature Detector

An alternative method for the detection of primary signals is *Cyclostationary Feature Detection*. Signals to be transmitted are in general coupled with sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. This results in built-in periodicity. These modulated signals are characterized as cyclostationary because their statistics, as mean and autocorrelation, exhibit periodicity. This periodicity is introduced in the signal format so that the receiver can exploit it for parameter estimation such as carrier phase, timing or direction of arrival. These features are detected by analyzing a *spectral correlation function* (SCF) or *cyclic spectrum*.

The main advantage of this function is that overlapping features in the power spectrum density (PSD) are non-overlapping features in the cyclic spectrum. Different types of modulated signals that have identical PSD can have highly distinct SCF. Furthermore, stationary noise and interference exhibit no spectral correlation.

Analogous to conventional autocorrelation function, SCF can be defined as:

$$S_x^a(f) = lim_{T\to\infty} lim_{\Delta t\to\infty} \int_{-\Delta t/2}^{+\Delta t/2} \frac{1}{T} X_T\left(t, f + \frac{\alpha}{2}\right) X_T^*\left(t, f - \frac{\alpha}{2}\right) dt \tag{2.3}$$

where the finite time Fourier transform is given by:

$$X_T(t,\nu) = \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi\nu u}\, du \tag{2.4}$$

The parameter α is called the cycle frequency. If $\alpha = 0$ then SCF gives the PSD of the signal.

Because of all these properties cyclostationary feature detector can perform better than energy detector in discriminating against noise. On the other hand it is computationally complex and requires significantly large observation time.

2.2 Local Spectrum Sensing Limitation

Essentially Cognitive Radio does not have a direct measurement of a channel between Primary user receiver and transmitter and must base its decision on its local channel measurement to a Primary user transmitter. This type of detection is referred to as *Local Spectrum Sensing* where each Cognitive device behaves toward external stimuli in an isolated way.
The worst case hidden terminal problem would occur when the Cognitive Radio is shadowed, in severe multipath fading, or inside buildings with high penetration loss while in a close neighborhood there is a Primary user whose is at the marginal reception, due to its more favorable channel conditions. In this way, Cognitive Radio will cause interference to such Primary user.
Therefore spectrum sensing performance overall under low signal-to-noise rescue (SNR) is crucial for reasons above mentioned.
All this complicate the detection of Primary activity and consequently the choice of the appropriate treshold in the detector and leads to a trade off between *False Alarm Probability* P_{fa} and *Missing Detection Probability* P_{miss}: high false alarm probability produces low spectrum utilization by Secondary users; high missing detection probability increases interference to Primary user.
From above discussion we can see that *local spectrum sensing* can never surpass its limitation on detecting weak signal.
Hence *Cooperative Spectrum Sensing* (CSS) is needed for improoving spectrum utilization and the detection ability of CR nodes especially under low SNR situations .

Chapter 3

Cooperation in CR Networks

3.1 Overview

Local spectrum sensing deteriorate its performances under low SNR and cannot prevent the hidden terminal problem. In order to improve performances, Cognitive Radios are allowed to cooperate to sensing the spectrum.

A network of Cognitive Radio nodes scattered in different places exploits *space diversity* to improve probability of detection and spectrum utilization.

Since CR networks can be deployed both as an infrastructure network and an ad hoc network, two schemes for cooperative SS which are respectively distributed and centralized spectrum sensing were studied accordingly [6].

The centralized network is a network whose size is fixed by the coverage area of the access point or base station. The decentralized network has a size that can be scaled up more flexibility by allowing intermadiate nodes in the transmission path as a relay.

In the following we will analyze cooperation in centralized and decentralized cognitive networks and will give a look to three cooperative cognitive techniques object of studies in these last years.

3.2 Decentralized Cognitive Networks

For ad hoc CR network, it is appropriate to take the distributed cooperative SS scheme [7]. In this scheme CR nodes randomly form into a cooperative network in wich the spectrum sensing information is shared and exchanged among CR nodes. Because of the ad hoc formation of the distributed CR network, it is proper that each CR node independently detects the PU and gives out its decision results about spectrum holes.

Consequently each CR node can receives *locally* the detection decision from other nodes. At this point each CR node can apply a fusion rule on the received decions to make its final detection decision.

Normally the decision fusion rule of all SS decision can be the k out of N rule: if k or more nodes decide the hypotheses H_1, then the globe decision will be H_1.

When $k = 1$, the k out of N rule becomes the OR rule, in which the final decision of spectrum holes comes from the union of all spectrum holes set by CR nodes.

If $k = n$ the fusion rule works as AND-rule, in wich the final spectrum holes comes from the intersection of all spectrum holes set.

When $k \geq (n+1)/2$, the fusion rule will become the majority fusion rule. The majority rule is used when the SNR levels of cooperative nodes are about in same levels. When only small part of CR nodes has high SNR, the cooperation of high SNR nodes will obtain better performance than all nodes to cooperate. If only one node has high SNR than other nodes, then it is proper that all other nodes should share the decisions made by the high SNR node.

Here is reported a neighbor exchange of spectrum sensing information scheme to increase the efficiency of spectrum sensing. Neighbors of a cognitive radio node means those cognitive radio nodes that can receive its signal directly. The procedure of this scheme is described as follows:

1. Every Cognitive Radio node has its own local spectrum sensing information. When a CR node initiates a communication, it first sends out a request with its own local spectrum sensing decision and local SNR indicator.
2. The neighbor nodes who can receive this request will give an answer to it and also send their local spectrum sensing decision with the local SNR indicator.
3. When the initial node receive its neighbor's spectrum sensing information, it will act as decision fusion center for the final decision of spectrum holes.
4. The fusion center first compares the SNR level from CR nodes and makes the decision fusion from the high SNR nodes. When all SNR are in same level, the majority fusion rule is taken.
5. After the initial node makes the final choise of spectrum from the fusion rule, it should announce its occupation of the spectrum holes to its neighbors to avoid contention and interference from them.
6. When neighbor nodes receive the occupation announcement, they will save this information in their memory. If neighbor nodes sense the new PU of the occupied spectrum holes, they can inform the occupier to vacate the occupied licensed channels.

A decentralized network offers more scalability towards the number of nodes but requires, on the other hand, more signalling and computational charge to the single node.

3.3 Centralized Cognitive Networks

When the network is infrastructure based there has to be a base station or access point providing connection to a backbone connection, as typically found in Internet access networks.
For this type of networks, the central station of the existing communication system broadcasts the frequency resource information for the secondary users, which are responsible only for sensing spectrum utilization information in their neighborhood and feedback the utilization information to the base system through the uplink transmission.
In downlink transmission, the base station, using the spectrum feedback side-information, decides which user accesses to the channel.
Centralized networks are less scalable respect to the previous ones but offers a better managment about signalling and sensing information overall in cases where local zones suffer low SNR conditions.

3.4 Cooperation Techniques

Through the literature related to this field of research, today one can define two main cooperative cognitive techniques.

- *Cooperative Transmission* in Cognitive Radio;
- *Cooperative Sensing* in Cognitive Radio.

3.4.1 Cooperative Transmission

Cooperative transmission in its basic forms refers to the information theoretic model of the relay channel, where one secondary node *(the relay)* forwards the transmission of a primary or secondary node *(the* *source)* towards its intended destination. Relaying through space diversity leads to performance advantages cause primary or secondary nodes are aided in their respective tasks; this gives:

- *power gains*, in particular if the relay happens to be in a convenient location, tipically halfway between source and destination;
- *diversity gains*, thanks to the double path followed by the signal (direct source-destination and relay transmissions).

Cooperative Transmission Between Secondary Users

In this scenario, a secondary user acts as relay for the transmission of another secondary terminal *(source)* to a predefined destination, usually a common receiver. Since secondary nodes need to continously monitor the channel for possible transmissions by the primary an interestingly proposal is to use relaying to enhance the sensing process of the same source. The main idea is to let the secondary relay node *amplify and forward* the received signal since the latter contains not only the transmission from the secondary source, but also, if present, the signal from the primary. This forwarding then allows the same initial secondary source, which can listen to the relaying too, to improve the local detection of the primary user in a scenario where the relay is placed approximately halfway between primary and secondary source.
In [8] a two-user cognitive radio network is considered. The network achieve diversity gain by allowing the user to cooperate. A possible implementation of a cooperative protocol in a TDMA system is considered. Cooperative protocols are of two kinds: 1) *Amplify-and-forward* (AF) and 2) *Decode-and-forward* (DF). It is shown that the

AF protocol, in which the relay transmits the signal obtained from the transmitter without any processing, achieves full diversity.

In the problem formulation all users experiences Rayleigh fading that is indipendent from user to user. If a signal x is sent, the received signal y is given by

$$y = fx + w \tag{3.1}$$

where the fading coefficient f and the additive noise w are modelled as independent complex Gaussian random variables. It is assumed that there is a centralized controller (capable of both receiver and sending) with which all the cognitive users communicat; each user has access to its channel state information. The two cognitive radio users U_1 and U_2 operate in a fixed TDMA mode for sending data to the common receiver as shown in Figure 3.1.
Supposed that a primary user starts using the band, the two cognitive users need to vacate the band as soon as possible to make way for the licensed user. However, the detection time becomes significant if one of the users, say U_1, is far away from the primary user and the signal received from the primary user is so weak that the cognitive users U_1 takes a long time to sense its presence. Cooperation between cognitive users can reduce the detection time of the ”weaker” user thereby improving the ”agility” of the overall network. The cognitive users, U_1 and U_2, are allowed to cooperate, with U_2 acting as a relay for U_1. U_1 and U_2 transmit in successive slots following the AF protocol as shown in Figure 3.2.
Accordingly in time slot T_1, U_1 transmits to the common receiver (ordinary link) and U_2 listens. In time slot T_2, U_2 relays (Amplify-and-forward mode) trasmission of T_1 to the common receiver (relay link). So U_1 listens to the eventual presence of the primary also thanks to

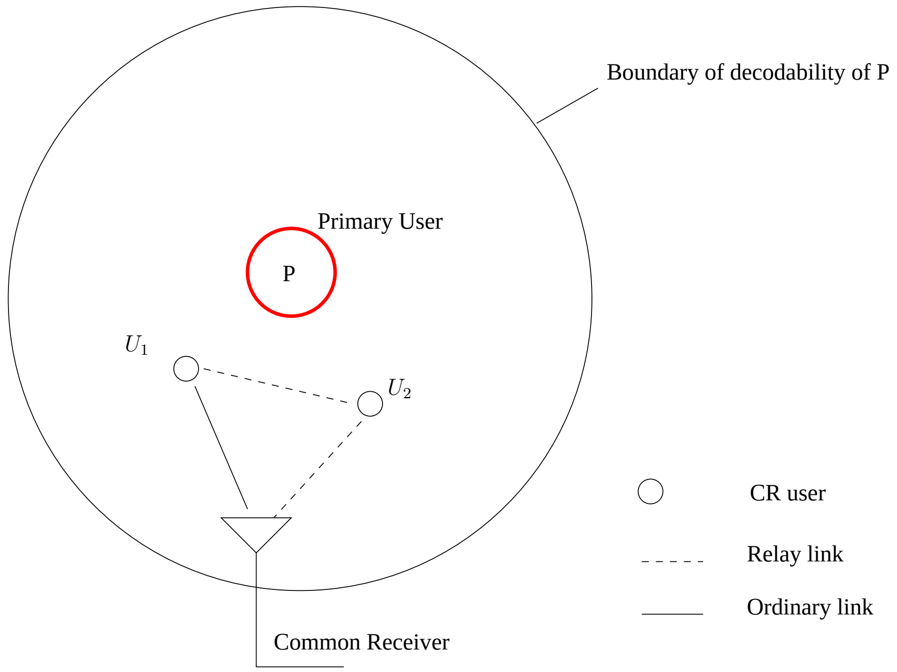

Figure 3.1 Cooperative transmission between secondary users in cognitive network.

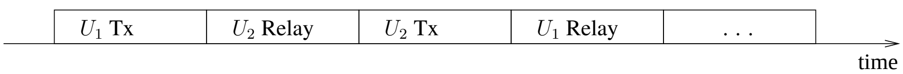

Figure 3.2 Relay protocol used.

its relayed transmission (relay link). Unknown to both these users, there is a primary user whose presence must be detected as soon as possible. In time slot T_1 the signal received by U_2 from U_1 is given by

$$y_2 = \theta h_{p2} + a h_{12} + w_2 \tag{3.2}$$

where h_{pi} denotes the istantaneus channel gain between the primary user and U_i, h_{12} denotes the istantaneus channel gain between U_1 and U_2, w_2 denotes the additive Gaussian noise, a denotes the signal sent from U_1 and θ denotes the primary user indicator; $\theta = 1$ implies presence of the primary user and $\theta = 0$ implies its absence. If the transmit power constraint of U_1 is P then,

$$E\left\{|y_2|^2\right\} = PG_{12} \tag{3.3}$$

where $G_{12} = E\left\{|h_{12}|^2\right\}$ refers to the channel gain between the users U_1 and U_2. Since h_{p2}, h_{12} and w_2 are assumed independent, we have

$$E\left\{|y_2|^2\right\} = \theta^2 P_2 + PG_{12} + 1 \tag{3.4}$$

where $P_i = E\left\{|h_{pi}|^2\right\}$ referes to the received signal power at U_i from the primary user. In time slot T_2, the relay user, U_2, relays the message from U_1 to the common receiver. The relay user has a maximum power constraint $\tilde{P}$. Hence it measures the average received signal power and scales it appropriately so that its power constraint $\tilde{P}$ is satisfied. In time slot T_2, when U_2 is relaying the message of U_1 to the receiver, U_1 also listens to its own message. The signal received by U_1 from U_2 is given by

$$\begin{aligned} y_1 &= \sqrt{\beta_1} y_2 h_{12} + \theta h_{p1} + w_1 \\ &= \sqrt{\beta_1} h_{12} \left(\theta h_{p2} + a h_{12} + w_2\right) + \theta h_{p1} + w_1 \end{aligned} \tag{3.5}$$

where h_{p1} is the istantaneous channel gain between the primary user and U_1, w_1 is additive Gaussian noise, and β_1 is a scaling factor used by U_2 to relay the information to the common receiver.
After the message component is cancelled, the user U_1 is left with the signal

$$Y = \theta H + W \tag{3.6}$$

where $H = h_{p1} + \sqrt{\beta_1} h_{12} h_{p2}$ and $W = w_1 + \sqrt{\beta_1} h_{12} w_2$.
The detection problem can be now formulated as follow:

Given the observation

$$Y = \theta H + W, \tag{3.7}$$

the detector decides on

$$H_1 : \theta = 1,$$

or

$$H_0 : \theta = 0.$$

This standard detection problem has been studied using an energy detector and results proved an improved overall probability of detection against the case in which the nodes operate individually.
In [9] a multiuser network is considered. In this case cooperation among more than two nodes performs better only at the cost of great computational complexity. The idea is to create couple of nodes in which the one with better condition towards the primary node is elected as relaying node.
However problems may arise when the network has no simmetry around the primary transmitter or if a relaying node has to aid more than one node, augmenting its charge.

Cognitive Relay

A different form of cooperative transmission is the *cognitive relay* [10] [11], where a secondary users has the possibility to relay the traffic of a primary transmitter towards the intended destination as shown in Figure 3.3.
Helping the primary to increase its throughput entails a diminished transmission time of the primary, which leads to more transmission

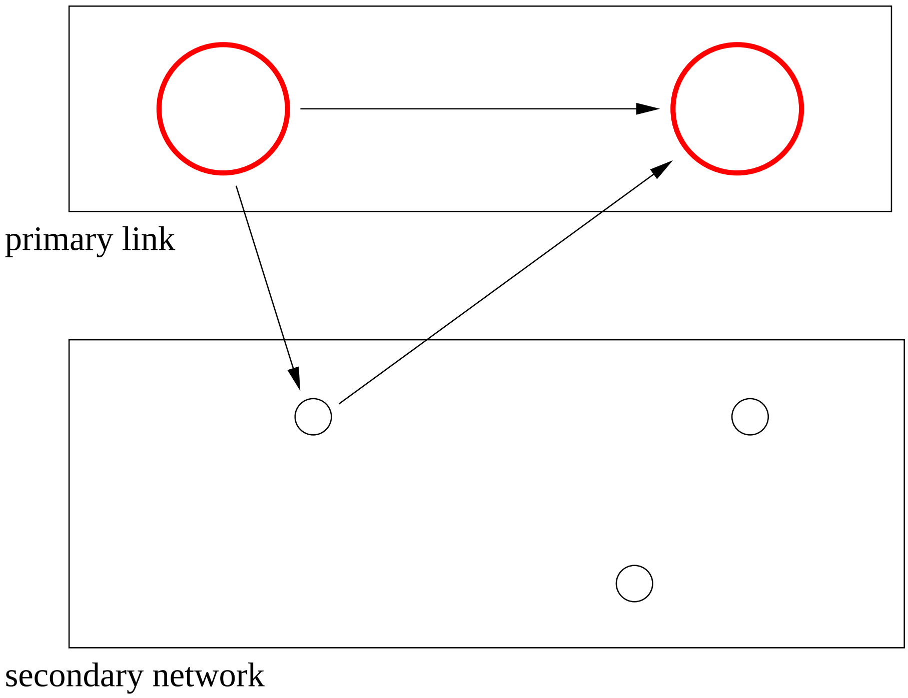

Figure 3.3 Cognitive relay approach for a simple cognitive wireless network with one primary link and a secondary network.

opportunities for the secondary. Therefore, cognitive relaying pursues an enhanced throughput by increasing the probability of transmission opportunities. A simple scenario presents one primary and one secondary link where the transmitter may act as relay in order to show the advantages of cognitive relaying.
Referring to Figure 3.4, both primary and secondary transmitting nodes have a queque in which incoming packets are stored. All packets have the same number of bits, and their transmission time coincides with a time slot.
The arrivals of packets at each transmitting station are indipendent and stationary processes, with λ_P (packets/slot) being the mean arrival rate at the primary queque and λ_S (packets/slot) the mean arrival

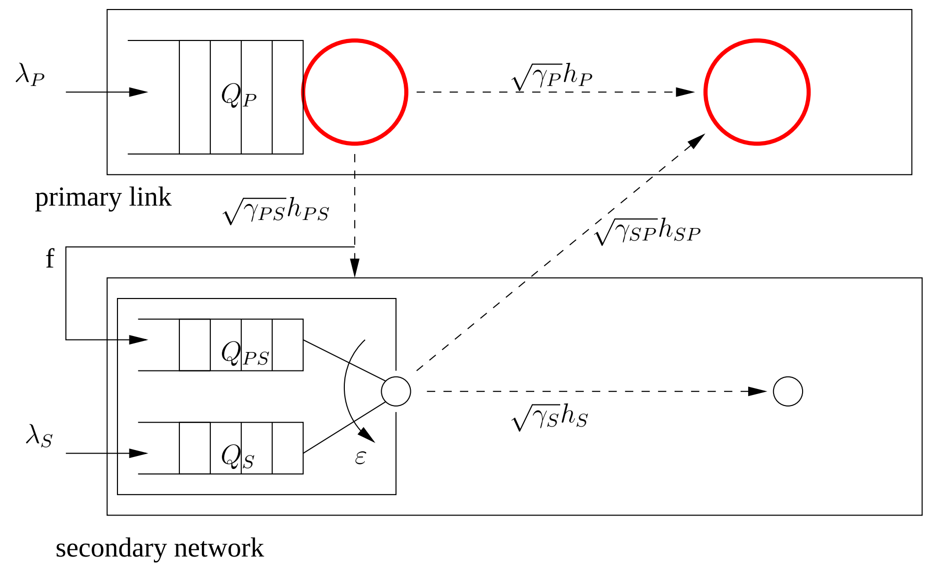

Figure 3.4 A simple cognitive relay model with one primary and one secondary links.

rate at the secondary queque.

The primary transmitter accesses the channel whenever it has a packet in its queque $Q_P(t)$ at the beginning of the slot t, being oblivious to the presence of the secondary link. Whenever a primary packet is not correctly received by its intended destination but is instead decoded at the secondary transmitter, the latter has the choise to store the packet in a separate queque $Q_{PS}(t)$ for later forwarding to the same primary destination (*cognitive relaying*).

Each primary receiving node sends to the respective primary transmitting node an ACK message in case of a correct reception or a NACK message in case of an erroneus reception. A packet reception error requires retransmission.

On the contrary, the secondary transmitter sends a packet to its destination in a given slot only if it senses an idle channel according to the spectrum sensing scheme and if it has a packet to transmit in its queque $Q_S(t)$ and $Q_{PS}(t)$. In this case it transmits a packet from the queque $Q_S(t)$ containing its own packets with scheduling probability ε or from the queque $Q_{PS}(t)$ with complementary probability $1 - \varepsilon$.

The secondary transmitter adapts its transmission mode to best accomplish two conflicting goals:

- making its activity transparent to the primary link;
- maximize its own stable throughput μ_S.

Cognitive relaying aims at enhancing the secondary throughput via the increase of transmission opportunities for primary nodes. Similarly to the previous technique it should be noted that these goals are achieved by increasing the overall energy consumed by secondary nodes, since these ones have to deliver not only their traffic but also that one of primary nodes.
Moreover must be noted that in this scenario secondary users has to know primary transmissions.

3.4.2 Cooperative Sensing

A simplified approach is to allow CR nodes to collaborate sharing only their sensing decision about the presence of a Primary node, avoiding in this way communication overhead as in previous two techniques.
As regards the channel model assumptions, two kinds of solutions have been studied in literature: a trivial one and a clustered one.

Trivial Solution

In scenarios with shadowing/fading problems, performance of energy-detector degrades and local spectrum sensing is not so efficient as in

ideal Primary-Secondary channel conditions.
Cooperation improves spectrum sensing [12]. It is performed in a hierarchical way:

1. Each CR node performs local spectrum sensing measurements independently and then makes a binary decision

2. All the cognitive users forward their binary decisions to a common receiver

3. The common receiver combines those binary decision to infer the absence or presence of the Primary user in the observed frequency band according to a decision fusion rule.

The system structure of the proposed method is illustrated in Figure 3.5.
If the channels between cognitive users and the common receiver are perfect and the OR decision fusion is employed at the common receiver, the false alarm probability Q_f, the detection probability Q_d and the missing probabilty Q_m of the collaborative scheme are given by

$$Q_f = 1 - \prod_{i=1}^{N}(1 - P_{f,i}) \tag{3.8}$$

$$Q_d = 1 - \prod_{i=1}^{N}(1 - P_{d,i}) \tag{3.9}$$

and

$$Q_m = 1 - \prod_{i=1}^{N} P_{m,i} \tag{3.10}$$

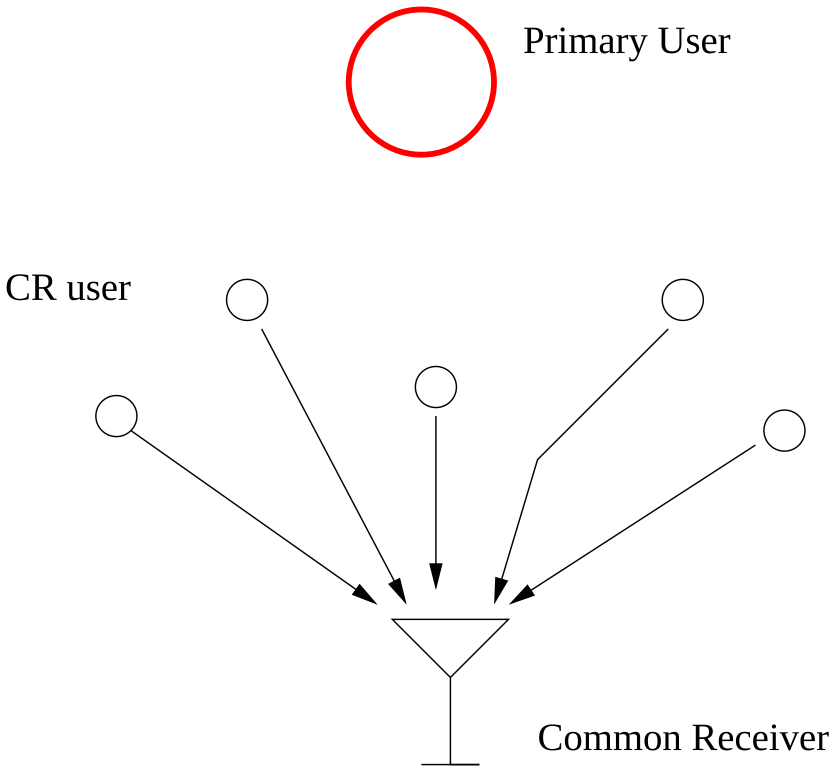

Figure 3.5 Cooperative Spectrum Sensing scheme: Trivial Solution.

where N is the number of cognitive users and $P_{f,i}$, $P_{d,i}$, $P_{m,i}$ are the false alarm probability, the detection probability and the missing probability for the ith cognitive user, respectively.

If the Primary-Secondary channel is affected by *Rayleigh fading*, following the analysis in [13], previous probabilities are given by:

$$P_{f,i} = \mathbf{E}_i[\text{Prob}\{H_1|H_0\}] = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)} \tag{3.11}$$

$$
\begin{aligned}
P_{d,i} &= \mathbf{E}_{\gamma,i}[\text{Prob}\{H_1|H_1\}] \\
&= e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!}\left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\bar{\gamma}_i}{\bar{\gamma}_i}\right)^{u-1} \\
&* \left[e^{-\frac{\lambda}{2(1+\bar{\gamma}_i)}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!}\left(\frac{\lambda\bar{\gamma}_i}{2(1+\bar{\gamma}_i)}\right)^n \right] \qquad (3.12)
\end{aligned}
$$

and

$$P_{m,i} = 1 - P_{d,i} \qquad (3.13)$$

where H_0 and H_1 denote the absence and the presence of the primary user, respectively, $\bar{\gamma}_i$ denotes the average SNR at the ith CR , $\mathbf{E}_{\gamma,i}[\cdot]$ represents the expectation over the random variable γ_i, Prob$\{\cdot\}$ stands for the probability, $\Gamma(\cdot,\cdot)$ is the incomplete gamma function and $\Gamma(\cdot)$ is the gamma function, λ is the threshold of the energy detector and $u = TW$ is the time bandwidth product.
$P_{f,i}$ is indipendent of γ_i since under H_0 there is no Primary signal present. On the other hand $P_{d,i}$ is conditioned by γ_i which has an exponential distribution under Rayleigh fading and the formula above is a closed-form of the averaging $P_{d,i}$ over γ probability distribution function.
This approach is clearly robust to possible unbalance of the channel qualities of different secondary users and shows to achieve a drastic improvement of the receiving operating curve.

The issue is that model is that in practice the reporting channel between CR node and the Common Receiver may experience Rayleigh fading too, which will deteriorate the performance of the cooperative spectrum sensing.

Let $P'_{f,i}$ denote the probability of receiving H_1 at the common receiver (after decoding) when the ith cognitive radio sends H_0 and $P'_{m,i}$ denote the probability of receiving H_0 at the common receiver (after decoding) when the ith cognitive radio sends H_1. Then, Q_f and Q_m are

$$Q_f = 1 - \prod_{i=1}^{N} \left[(1 - P_{f,i}) \left(1 - P'_{f,i}\right) + P_{f,i} P'_{m,i} \right], \tag{3.14}$$

$$Q_m = \prod_{i=1}^{N} \left[P_{m,i} \left(1 - P'_{f,i}\right) + (1 - P_{m,i}) P'_{m,i} \right]. \tag{3.15}$$

It can be seen that $P'_{f,i} = P'_{m,i}$,so $P_{e,i} = P'_{f,i} = P'_{m,i}$ can be used to represent the reporting error probabilty. From the latter equations, it is known that Q_m is degraded by the imperfect reporting channel and Q_f is bounded by the reporting error probability. This means that spectrum sensing cannot be succesfully conducted when the desired Q_f is smaller than the bound $\bar{Q}_f$.

Cluster-Based Solution

In order to reduce the reporting error probability $P_{e,i}$ and improve the sensing performance, one can take advantage of multiuser diversity through a cluster-based cooperative spectrum sensing [14].
By taking advantange of the indipendent fading channels between Common Receiver and CR nodes , multiuser diversity can be exploited.
In this case two assumptions are taken:

- the istantaneous channel state information of the reporting channel is available at the cognitive users;

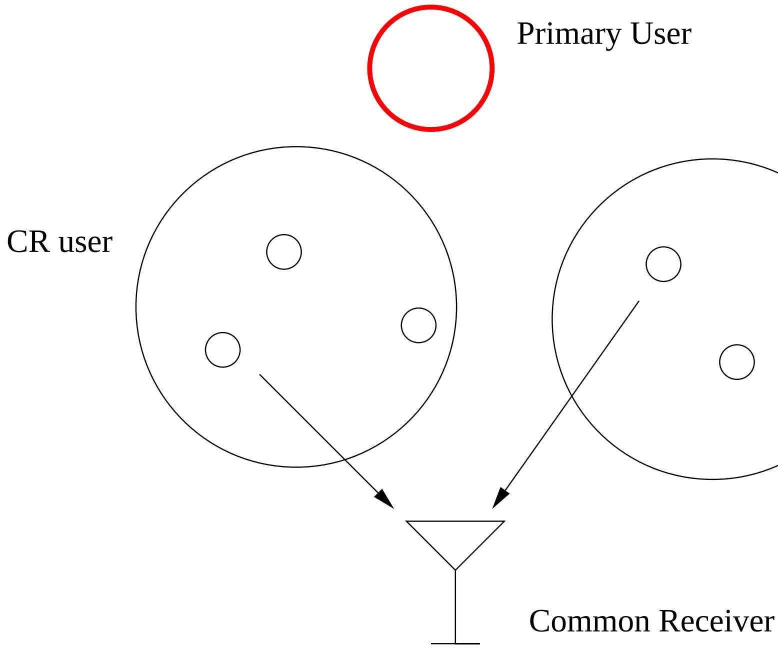

Figure 3.6 Cluster-based cooperative spectrum sensing in cognitive radio systems.

- The channel between any two users in the same cluster is perfect since they are close to each other.

The system structure of the proposed method is illustrated in Figure 3.6.
The solution can be summarized through the following steps:

1. All cognitive radios are clustered into a few group according to a clustering algorithm [15] [16].
2. A cluster head is choosen in each cluster according to the highest SNR of the reportig channels.
3. Every cognitive radio j in cluster i performs the local spectrum sensing: it collects the energy $O_{i,j}$ and sends a local observation

$G_{i,j}$ to the cluster head, where $G_{i,j}$ is related to $O_{i,j}$ by a function Ω

$$G_{i,j} = \Omega\left(O_{i,j}\right), i = 1, 2, ..., K, j = 1, 2, .., N_i \tag{3.16}$$

K is the number of clusters and N_i is the number of cognitive users in the ith cluster.

4. The cluster head receives those local observations in the same cluster and then make a preliminary cooperative decision B_i according to some fusion function Φ, as

$$B_i = \Phi\left(G_{i,1}, G_{i,2}, ..., G_{i,N_i}\right), i = 1, 2, ..., K \tag{3.17}$$

5. Only cluster heads are required to report to the common receiver their preliminary cooperative decisions B_i for all i.

6. Based on these decisions B_i, the common receiver will make a final decision H according to a fusion function Ψ, as

$$H = \Psi\left(\hat{B}_1, \hat{B}_2, ..., \hat{B}_K\right) \tag{3.18}$$

where $\hat{B}_1, \hat{B}_2, ..., \hat{B}_K$ are the recovered signals (1 or 0) at the common receiver (after decoding).

Different fusion functions in wireless sensor networks can be used in the common receiver. In order to avoid interference to the primary user, the cognitive users access the spectrum when all the reported decisions demonstrate that the primary user is absent. Otherwise, one assume that the primary user is present. For istance, using the OR-rule in the common receiver, the final decision is:

$$\Psi : H = \begin{cases} 1 & \text{if} \sum_{i=1}^{K} \hat{B}_i \geq 1 \\ 0 & \text{otherwise.} \end{cases} \tag{3.19}$$

Let $Q_{f,i}$, $Q_{d,i}$ and $Q_{m,i}$ denote the false alarm probability, the detection probability and the missing probability of the cluster head in cluster i, respectively. Let $Q_{e,i}$, denote the error probability that the cluster decision B_i is reported to the common receiver but the decision $\hat{B}_i$ is obtained. Then, the system performance of the cluster-based cooperative spectrum sensing can be evaluated as follows:

$$Q_f = 1 - \prod_{i=1}^{K} \left[\left(1 - Q_{f,i}\right) \left(1 - Q_{e,i}\right) + Q_{f,i} Q_{e,i} \right] \tag{3.20}$$

$$Q_m = \prod_{i=1}^{K} \left[Q_{m,i} \left(1 - Q_{e,i}\right) + \left(1 - Q_{m,i}\right) Q_{e,i} \right] \tag{3.21}$$

Because the cluster decision B_i is sent through the best channel among all N_i reporting channels in cluster i, a diversity gain of N_i is obtained. Cluster i is taken as an example to derive the reporting error probability $Q_{e,i}$ and show such a diversity enhancement. Let $\rho_{max,i}$ denote the channel SNR from the cluster head to the common receiver, i.e.

$$\rho_{max,i} = max \left(\rho_{i,1}, \rho_{i,2}, ..., \rho_{i,N_i}\right) \tag{3.22}$$

where $\rho_{i,j}$ denotes the channel SNR from user j in cluster i to the common receiver which is exponentially distributed with the same means value $\bar{\rho}_i$ because they are close to each other.

$$f(\rho_{i,j}) = \frac{1}{\bar{\rho}_i} e^{-\frac{\rho_{i,j}}{\bar{\rho}_i}} \tag{3.23}$$

The probability density function of $\rho_{max,i}$ instead is:

$$f(\rho_{max,i}) = \frac{N_i}{\bar{\rho}_i} e^{-\frac{\rho_{max,i}}{\bar{\rho}_i}} \left(1 - e^{-\frac{\rho_{max,i}}{\bar{\rho}_i}}\right)^{N_i - 1} \tag{3.24}$$

For a given $\rho_{max,i}$, the error probability, assuming BPSK for simplicity, is:

$$Q_{e,i|\rho_{max,i}} = Q\left(\sqrt{2\rho_{max,i}}\right) \tag{3.25}$$

where $Q(\cdot)$ is the $\mathcal{Q}$-function. Therefore, the average error probability over Rayleigh fading channels is given by:

$$\begin{aligned} Q_{e,i} &= \int_0^\infty Q_{e,i|\rho_{max,i}} f(\rho_{max,i})\, d\rho_{max,i} \\ &= \sum_{m=0}^{N_i-1} \begin{pmatrix} N_i - 1 \\ m \end{pmatrix} (-1)^{N_i-m-1} \frac{N_i}{2(N_i-m)} \\ &* \left(1 - \sqrt{\frac{\bar{\rho}_i}{N_i - m + \bar{\rho}_i}}\right) \end{aligned} \tag{3.26}$$

It can be seen that, for the same SNR, with the increase of the number of the cognitive users N_i, the reporting error decreases. This means that a selection diversity N_i is achieved.
A cluster-based method for cooperative spectrum sensing perform some advantages:

- diversity gains proportional to the number of nodes per cluster
- lower energy consumption thanks to inter cluster information exchange.

Chapter 4

Energy Detector: Physical Model

4.1 Chapter overview

In many wireless applications, it is of great interest to check the presence and availability of an active communication link when the transmitted signal is unknown. In such scenarios, one appropriate choise consists of using an *energy detector* wich measures the energy of the received waveform over an observation time window. The object of this chapter, referring to [13], is to derive the physical model of a CR node, that will be used in the simulation environment of this work, together with the probability of detection (P_d) and the probability of false alarm (P_f). These probabilities can be obtained relying on the sampling theorem which states that a received sampled signal, of duration T, of a process which has bandwidth W, is described approximately by a set of $2TW$ samples.

4.2 System model

Before describing the system model under consideration, a list is described with the main notation that will be used in this chapter .

- $s(t)$: signal waveform.
- $n(t)$: noise waveformwich is modewlled as a zero-mean white Gaussian random process.
- N_{01} : one-sided noise power spectral density.
- $N_{02} = \frac{N_{01}}{2}$: two-sided noise power spectral density.
- Es : signal energy = $\int_0^T s_2(t)\, dt$.
- $\gamma = \frac{E_s}{N_{01}}$: signal-to-noise ratio (SNR).
- $\bar{\gamma}$: average SNR.
- λ : energy threshold used by the energy detector.
- T : observation time interval, seconds.
- W : one-sided bandwidth (Hz).
- $u = TW$: time bandwidth product.
- f_c : carrier frequency.
- P_d : probability of detection.
- P_f : probability of false alarm.
- $P_m = 1 - P_d$: probability of missing.
- H_0 : hypothesis 0 corresponding to no signal transmitted.
- H_1 : hypothesis 1 corresponding to signal transmitted.
- $N(\mu, \sigma^2)$: a Gaussian variate with mean μ and variance σ^2.
- χ^2_α : a central chi-square variate with α degrees of freedom.
- $\chi^2_\alpha(\beta)$: a noncentral chi-square variate with α degrees of freedom and noncentrality parameter β.

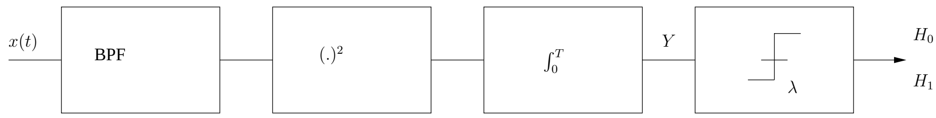

Figure 4.1 Block diagram of an energy detector.

To describe the system model we can consider the block diagram of an energy detector, Figure 4.1.
Spectrum sensing can be described as a decision binary problem. The received signal $x(t)$ takes the form

$$x(t) = \begin{cases} n(t) & , H_0 \\ h\,s(t) + n(t) & , H_1 \end{cases} \tag{4.1}$$

where $h = 0$ or 1 under hypothesis H_0 or H_1, respectively. The received signal is first pre-filtered by an ideal bandpass filter with transfer function

$$H(f) = \begin{cases} \frac{2}{\sqrt{N_{01}}} & , |f - f_c| \leq W \\ 0 & , |f - f_c| > W \end{cases} \tag{4.2}$$

to limit the average noise power and normalize the noise variance. The output of this filter is then squared and integrated over a time interval T to finally produce a measure of the energy of the received waveform. The output of the integrator denoted by Y will act as the test statistic to test the two hypotheses H_0 and H_1. It's convenient to compute the false alarm and detection probabilities using the quantity

$$Y = \frac{1}{\sqrt{N_{02}}} \int_0^T y^2(t)dt \tag{4.3}$$

According to the sampling theorem, the noise process can be expressed as

$$n(t) = \sum_{i=-\infty}^{+\infty} n_i \, sinc\left(2Wt - i\right) \tag{4.4}$$

where $sinc(x) = \frac{sin(\pi x)}{\pi x}$ and $n_i = n\left(\frac{i}{2W}\right)$, $n_i \sim N(0, \sigma_i^2)$ for all i.
Using the fact that

$$\int_{-\infty}^{+\infty} sinc(2Wt - i)\, sinc(2Wt - k)\, dt = \begin{cases} \frac{1}{2W} & , i = k \\ 0 & , i \neq k \end{cases} \tag{4.5}$$

we may write

$$\int_{-\infty}^{+\infty} n^2(t)dt = \frac{1}{2W} \sum_{i=-\infty}^{+\infty} n_i^2 \tag{4.6}$$

Over the interval $(0, T)$

$$n(t) = \sum_{i=1}^{2TW} n_i \, sinc\left(2Wt - i\right) \, , \; 0 < t < T \tag{4.7}$$

Similarly, the noise energy can be approximated as

$$\int_0^T n^2(t)dt = \frac{1}{2W} \sum_{i=1}^{2TW} n_i^2 \tag{4.8}$$

If we define

$$n_i' = \frac{n_i}{\sqrt{N_{01} W}} = \frac{n_i}{\sqrt{2WN_{02}}} \tag{4.9}$$

then the test or decision statistic Y can be written as

$$Y = \sum_{i=1}^{2TW} (n_i')^2 \tag{4.10}$$

Y can be viewed as the sum of the squares of $2TW$ standard Gaussian variates with zero mean and unit variance. Therefore, Y follows a central chi-square (χ^2) distribution with $2TW$ degrees of freedom.
The same approach is applied when the signal $s(t)$ is present with the replacement of each n_i by $n_i + s_i$ where $s_i = s\left(\frac{i}{2W}\right)$. Now consider the input $y(t)$ when the signal $s(t)$ is present

$$y(t) = \sum_{i=1}^{2TW} (n_i + s_i)\, sinc\,(2Wt - i) \tag{4.11}$$

The energy of $y(t)$ in the interval $(0, T)$ is

$$\int_0^T y^2(t)dt = \frac{1}{2W} \sum_{i=1}^{2TW} (n_i + s_i)^2 \tag{4.12}$$

Under the hypothesis H_1, the test statistic Y is:

$$Y = \frac{1}{N_{02}} \int_0^T y^2(t)dt = \sum_{i=1}^{2TW} (n_i' + s_i')^2 \tag{4.13}$$

This sum have a noncentral chi-square distribution with $2TW$ degrees of freedom and a non-centrality parameter 2γ :

$$2\gamma = \sum_{i=1}^{2TW} (s_i')^2 = \frac{1}{N_{02}} \int_0^T s^2(t)dt = \frac{E_s}{N_{02}} \tag{4.14}$$

where 2γ, the ratio of signal energy to noise spectral density, provides a convenient definition of signal-to-noise-ratio. The decision statistic in this case can be described as follow

$$Y \sim \begin{cases} \chi^2_{2u} & , H_0 \\ \chi^2_{2u}(2\gamma) & , H_1 \end{cases} \tag{4.15}$$

The probability density function (PDF) of Y can be written as

$$f_Y(y) = \begin{cases} \frac{1}{2^u\Gamma(u)} y^{u-1} e^{-\frac{y}{2}} & , H_0 \\ \frac{1}{2}(\frac{y}{2\gamma})^{\frac{u-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{u-1}(\sqrt{2\gamma y}) & , H_1 \end{cases} \tag{4.16}$$

where $\Gamma(\cdot)$ is the gamma function and $I_{u-1}(\cdot)$ is the $(u-1)$th-order modified Bessel function of the first kind.
The probability of false alarm P_f for a given threshold λ is given by

$$P_f = Pr(Y > \lambda | H_0) = Prob\left\{\chi^2_{2u} > \lambda\right\} \tag{4.17}$$

For the same threshold level λ, the probability of detection P_d is given by

$$P_d = Pr(Y > \lambda | H_1) = Prob\left\{\chi^2_{2u}(2\gamma) > \lambda\right\} \tag{4.18}$$

χ^2_{2u} and $\chi^2_{2u}(\lambda)$ are the central and noncentral chi-square variable with $2TW$ degrees of freedom, respectively. While , extensive tables exist for the chi-square distribution, the noncentral chi square has not been as extensively tabulated. Approximations can be used to replace the noncentral chi-square with a central chi-square having a different number of degrees of freedom and a modified threshold level.

4.3 Detection for Large Time-Bandwidth Product

It is useful to have the means for rapidly computing false alarm and detection probability for given TW and 2γ.
There are nomograms suitable for values of $2TW \leq 250$. For large values, and this is the useful case for the physical model of this work, the *Gaussian approximation* can be applied to the probability density

function of the test statistic Y, under either noise alone or signal plus noise conditions.
The appropriate expressions are found by using a normal variate, with proper mean and variance, for finding the probability of exceeding the threshold λ.
Under the no-signal condition Y is the sum of $2TW$ statistically independent random variables. Thus the mean and the variance of the sum are $2TW$ and $4TW$ respectively. Therefore, Y is distributed as a Gaussian variate $N(2TW, 4TW)$ and the false alarm probability is given by

$$\begin{aligned} P_f &= \frac{1}{\sqrt{8\pi TW}} \int_Y^{\infty} e^{-\frac{(x-2TW)^2}{8TW}} dx \\ &= \frac{1}{2} erfc\left[\frac{\lambda - 2TW}{2\sqrt{2}\sqrt{TW}}\right] \end{aligned} \tag{4.19}$$

Under the signal plus noise condition Y leads to a mean value of $2TW + 2\gamma$ and to a variance of $4(TW + 2\gamma)$ giving a Gaussian variate $N(2TW+2\gamma, 4(TW+2\gamma))$. The probability of detection is given by

$$P_d = \frac{1}{2} erfc\left[\frac{\lambda - 2TW - 2\gamma}{2\sqrt{2}\sqrt{TW + 2\gamma}}\right] \tag{4.20}$$

4.4 Detection and False Alarm Probabilities over AWGN Channels

In a non-fading environment where h is deterministic, probabilities of detection and false alarm are given by the following formulas [12]:

$$P_d = Pr(Y > \lambda | H_1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{4.21}$$

$$P_f = Pr(Y > \lambda | H_0) = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)} \tag{4.22}$$

where $u = TW$, λ is the threshold, 2γ is the non-centrality parameter, $\Gamma(\cdot)$ and $\Gamma(\cdot, \cdot)$ are complete and incomplete gamma function respectively and $Q_u(\cdot, \cdot)$ is the generalized Marcum Q-function, defined as

$$Q_u(a, b) = \int_b^{+\infty} \frac{x^u}{a^{u-1}} e^{-\frac{x^2+a^2}{2}} I_{u-1}(ax)\, dx \tag{4.23}$$

where $I_{u-1}(\cdot)$ is the modified bessel function of $(u-1)$-th order.

P_f is independent of γ since under H_0 there is no primary signal present. On the other hand the probability of detection P_d is conditioned on the instantaneous SNR γ.

4.5 Rayleigh fading channels

When h is varying due to shadowing/fading and $f_\gamma(x)$ is the probability distribution function of SNR under fading, average probability of detection (which with an abuse of notation is denoted by P_d) may be derived by averaging 4.21 over fading statistics

$$P_d = \int_x Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) f_\gamma(x)\, dx \tag{4.24}$$

Under Rayleigh fading channel the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by

$$f_\gamma = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}} \ , \ \gamma \geq 0 \tag{4.25}$$

The average P_d in this case can be evaluated by sobstituting f_γ in 4.24:

$$\begin{aligned} \bar{P}_d \ &= \ e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{u-1} \\ &* \ \left[e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})} \right]. \end{aligned} \tag{4.26}$$

Chapter 5

CSS: Model Implementation

5.1 Motivation and Innovation

This work, after having analized different solutions carried on by the literature on the argument of cognitive radio, proposes a novel approach to cooperative sensing to achieve two principal goals

- SENSING RELIABILITY: the secondary network has to minimize,during its activity, the interference towards primary licensed users.
- ENERGY EFFICIENCY: the secondary network has to minimize energy consumption for sensing operations and for its normal activity in order to maximize its life-time.

A possible scenario is a cognitive ad hoc network that works in a non-interfering way in the spectrum allocated to WiMax service where a primary transmitter is operating.
We assume channels from primary transmitter to secondary nodes are affected by Rayleigh fading whereas channels in the secondary networks are AWGN channels. Only secondary data traffic may interfere with primary activity while secondary sensing and control traffic

is sent on a separated interference-free channel.

The idea is to merge together in the secondary network a CLUSTERED approach and a *WEIGHTED* COOPERATIVE SPECTRUM SENSING as will be described in detail in the next section.

5.2 Clustered Hybrid Model

The main features of a *Clustered Hybrid Energy Aware Cooperative Spectrum Sensing* are explained below

- <u>CLUSTERIZATION</u>. The network is composed of cognitive nodes scattered in an area and sending informations to a Base Station (BS) that coordinates the activities. Grouping the nodes into clusters allows nodes to send informations at a much lower power toward their Cluster Head (CH) as regards the one they would use to send informations directly to the Base Station.

  This will leads locally to eventual lower levels of interference with primary users. Only CH are responsible to forward informations to the BS at higher power and to perform local spectrum sensing. In this way the other nodes or Common Nodes have very little charge and do not spend energy for sensing. Obviously CHs loose energy faster than Common Nodes, so a periodic Re-Clusterization is requested to extend network's life-time.

  The way a CH is elected or a clusterization is requested differs from system to system. For istance, in section 3.4.2, the election of a CH was tied to the sensing problem; it was the one with the best condition on the reporting channel toward the BS in order to avoid error in the received sensing informations. A re-clusterization instead was requested for energy needs of the same cluster head.

Here another approach is used.

- WEIGHTED CSS. In order to simplify the system and minimizing the consumption of energy, we use cooperative spectrum sensing in which cognitive nodes share only their one bit decision on the presence of the primary activity. The BS apply the majority fusion rule to the set of decisions sent by CHs and makes the final decision informing the whole network.

  The choise of CHs follows a particular metric for that each node obtain a weighted sum of two terms.

  The first one is related to the residual energy of the node to avoid the same to be elected CH too often and to consume its energy too fast as regards other nodes. A re-clusterization can be asked by a CH that has lost a certain part of its energy.

  The second one is related to its Reliability, i.e. how much that node is reliable in detecting the primary activity. This depends on the SNR the node measures when the primary is transmitting and is influenced by Rayleigh fading. Each node measures its Reliability during the *training phase* in which it compare its decisons with the ones taken by the BS (majority rule). The Reliability may vary in time leading a CH to take more often wrong decision. A re-clusterization can be asked by a CH that sees its Reliability diminishing.

The secondary network behaves in a centralized manner and during all its life-time it passes sequentially in three possible states, as it is shown in figure 5.1, with the BS that manages the temporal axis in

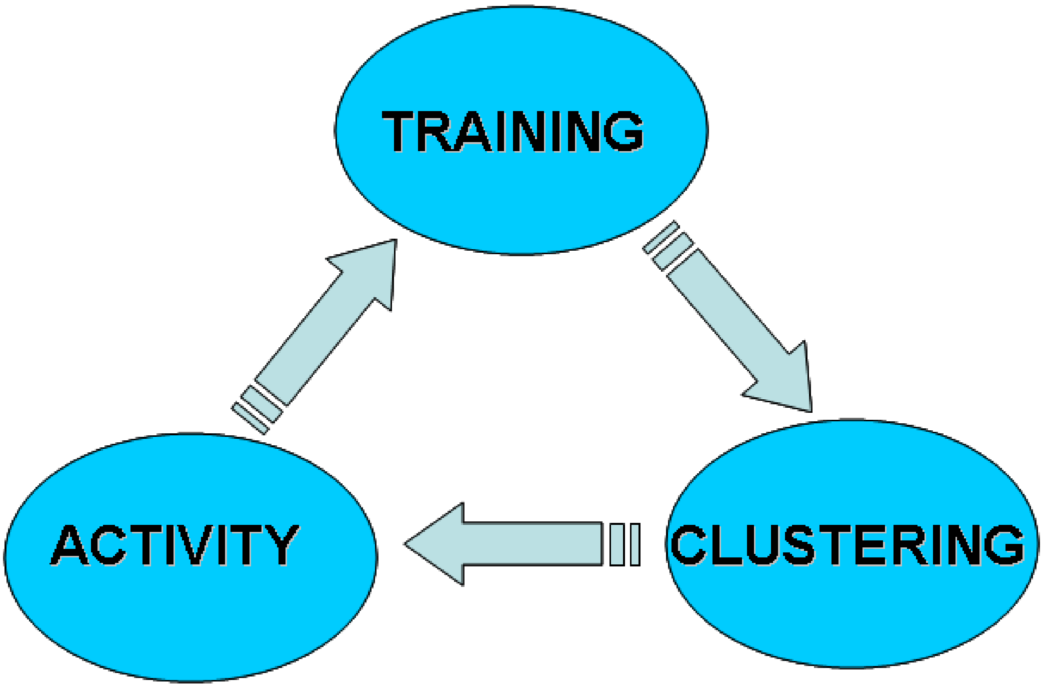

Figure 5.1 Passage of states in the secondary network

a slotted way as regards the sensing and contolr traffic. These three states completely describe the behaviour of the network and will be described below.

5.2.1 Training State

The *Training State* begins with a *"training startup"* message from the BS to the secondary networks and lasts 90 seconds.
The temporal axis is slotted. At the beginning of each slot, except the first, the BS applies the fusion majority rule and sends the final decision about the state of the channel: IDLE or BUSY as regards the primary activity.
During each slot, each node of the network update its Reliability (ini-

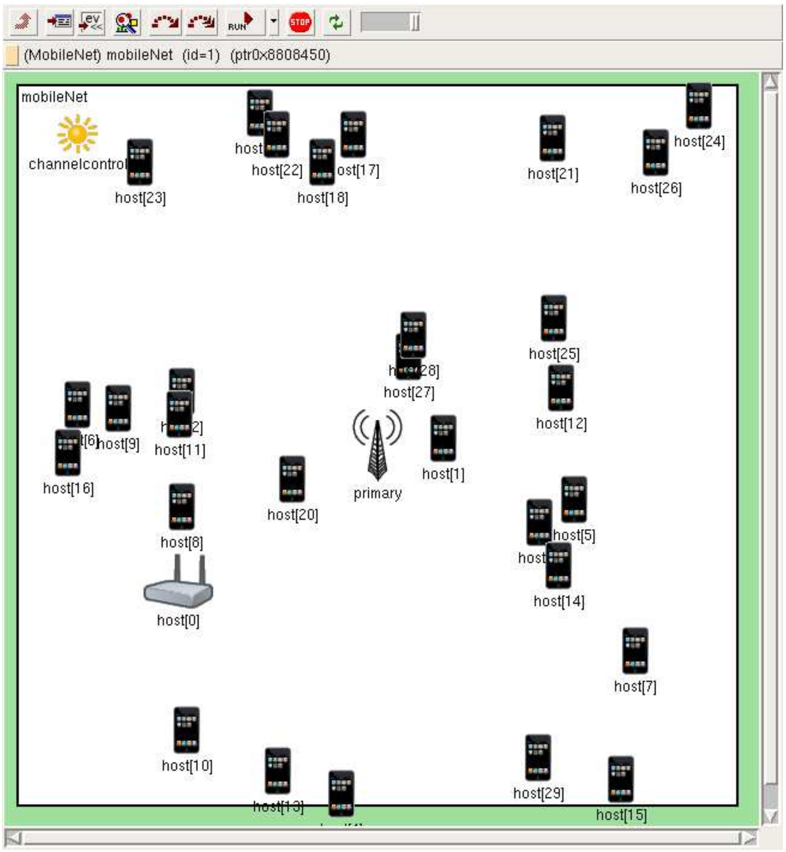

Figure 5.2 Secondary Network in Training State (Omnet++ Simulation Environment)

tially set at 0) comparing the decision it took in previous slot with the final decision received in the present one: when its decision is in accord with the final one, its Reliability gains one point, otherwise remains the same.

Moreover each node performs its local spectrum sensing inside that slot and sends its decision before the beginning of the next slot following a CSMA MAC protocol. For each node, the local detection problem is completely described by the three formulas of chapter 4 about P_f, P_d and γ, respectively 4.19, 4.20 and 4.25.

Figure 5.2 shows a secondary networks in training state with the BS,

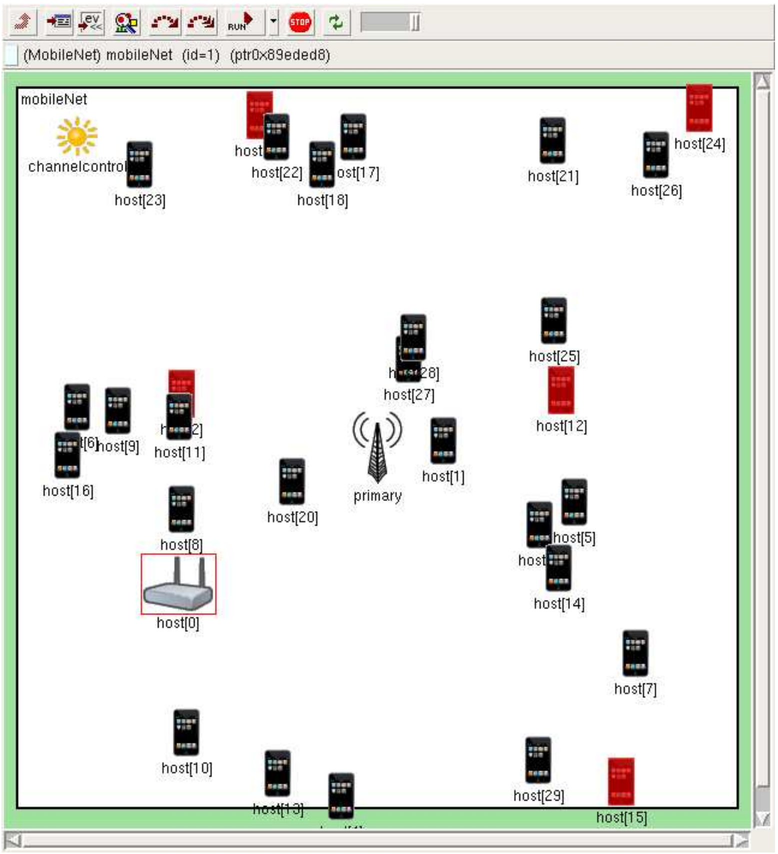

Figure 5.3 Final CHs: First Phase of Clusterization State(Omnet++ Simulation Environment)

the primary transmitter is in the center. The picture is a screenshot of the Omnet++ simulator, the one used for this work and will be described later.

5.2.2 Clustering State

The *Clustering State* begins with a *"clustering startup"* message from the BS to the secondary networks and lasts 30 seconds.
Each node calculate its total weight "Λ" in the following way

$$\Lambda = \epsilon * \frac{E_{residual}}{E_{total}} + \rho * R_{eliability} \tag{5.1}$$

Where $0 \leq \epsilon, \rho \leq 1$, with $\epsilon + \rho = 1$, are the weights assigned respectively to the Energy factor of the sum and to the Reliability one. Their value, i.e. the relevance to give to the two factors, will be object of analysis.
Reliability is given as number of correct decision as regards the final decisions divided the total number of decisions performed during the Training State. In this way also the two factors of the weighted sum are included betwen 0 and 1 and consequently $0 \leq \Lambda \leq 1$.
In this period a local exchange of control message takes place among neighbour nodes that transmit at a much lower power as regards the Training Period. This intra-cluster power will depend on the desired cluster range and will be object of performance analysis.
This period is divided into two phases of the same duration.

First phase

Each node,only if its Reliability is greater than 60%, transmits 3 times in a repetition way a *"tentative CH"* message containing its Total Weight Λ. It receives from its neighbours the same kind of messages and stores in a table the couples Address-Λ. At the end it looks up in the table the address of the node with the maximum Λ. If this address is equal to its address it becomes a CH, otherwise it cannot choose already the best node in its table as its CH because also that node could have in its table a third node better than him and hidden to the first one. The node cleans its table.
This phase is shown in figure 5.3 where the CH are the red nodes.

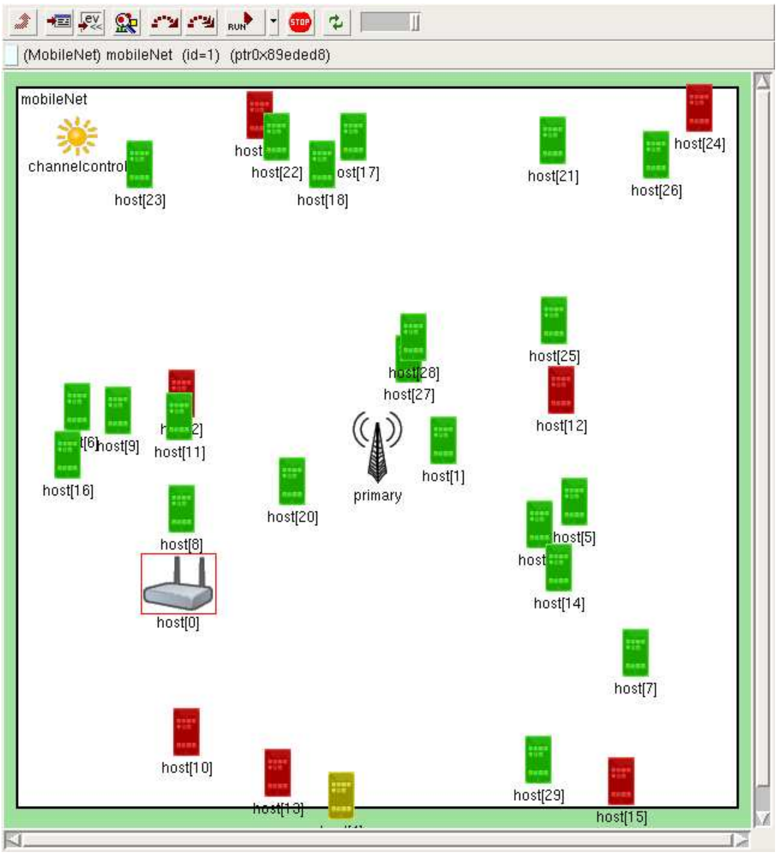

Figure 5.4 Network at the end of Clusterization State (Omnet++ Simulation Environment)

Second phase

The CHs send in their cluster range a *"final CH"* message. Each other node again stores in tits table the couples Address-Λ from eventual CHs in its cluster range. At the end it checks the table.

If it is not empty the node finds the address of the CH with the maximum Λ, choose it as its CH and stores its address to send to it its DATA message at the intra-cluster power during the last state. This is shown in figure 5.4 by the green nodes.

If it is empty this means the node is isolated from CHs. It checks its

Reliability. If it is greater than 60% the node becomes a CH: it will sends only its DATA messages and sensing decisions at the maximum power. This is shown in figure 5.4 by the new added red nodes. If it is lower than 60% it will send only DATA messages and at the maximum power during the last state. This is shown in figure 5.4 by the yellow nodes.

5.2.3 Activity

The *Activity State* begins with an *"activity startup"* message from the BS to the secondary networks and lasts till one CH sends to the BS a *"re-clusterization request"* message.
In this period the exchange of sensing messages is among the BS and the CHs, still organized in a slotted way. DATA message generated from Common Nodes are sent to the BS directly at the maximum power if they are isolated or to their CH at intra-cluster power if they have one. CHs relay DATA message of the Common Nodes they serve or send their own generated DATA message to the BS at maximum power.

At the beginning of each slot the BS advices the network about the channel state.
If the channel results BUSY, each node of the network stops sending DATA, only sensing message will continue to be exchanged in the control channel.
If the channel results IDLE, each node can send DATA. A preventive measure has been taken allowing a CH stopping relaying DATA also during an IDLE slot, if it senses the primary presence, without waiting the final decision for that very slot. If its decision is right it will avoid interfering with the primary at maximum power, otherwise it

will loose the possibility of sending DATA but the first task is avoiding interference. Neverthless Common Nodes will continue creating interference till the end of the actual slot but only locally and with a minimum impact thanks to the low level of power utilised.

A CH can request to the BS a re-clusterization in two cases

- ENERGY RE-CLUSTERIZATION: at the beginning of the Activity State each CH stores its energy. Every slot time it checks its energy status and if

  $$E_{residual} \leq E_{activitystartup} - \Delta E \tag{5.2}$$

  it does not send its sensing decision but the re-clusterization request.

  ΔE depends on the traffic load and grows proportionally to it to avoid too frequent re-clusterizations that will lead to an excessive loss of activity of the networks.

- RELIABILITY RE-CLUSTERIZATION: at the beginning of the Activity State each CH set its Reliability to 1. At the beginning of slot *n* each CH compare the received final decison with its decision in slot *n-1* and update its $R_{eliability}$ in the following way

  $$R_{eliability} = \begin{cases} min(R_{eliability} + \Delta R, 1) & ,correctCHdecision \\ R_{eliability} - \Delta R & ,wrongCHdecision \end{cases} \tag{5.3}$$

  If $R_{eliability} < 0.6$ the CH does not send its sensing decision but the re-clusterization request.

ΔR must be chosen properly: too big values lead to few possibilities of error for the single CHs and consequently too many re-clusterizations and a reduced activity, too low values lead to many possibilities of error for the single CHs and consequently too few re-clusterizations with a bad system Reliability during the activity.

Simulations in this work have been conducted with $\Delta R = 0.025$.

When the BS receive the re-clusterization request it starts a new Training State.

5.3 Basic Model

In next chapter the performances of the Clustered Hybrid Energy Aware Cooperative Spectrum Sensing model will be compared with the ones of a Basic Cooperative Model, in wich the decision about channel state is taken every slot as in the Clustered Model, but in this case only by a single node while the BS acts as a simple relay to inform the network about the decision taken.
Each node in sequence sense the channel and is responsible for all the network's behaviour.
It will sense the channel every $T_{slot}*N_{umberOfNodes}$ seconds. In this way the control traffic is reduced, but the system reliability suffers from the istantaneous conditions of that particular node toward the primary transmitter in a Rayleigh fading environment. This can cause delays in the detection if more than one node in sequence makes a wrong decision, on the other hand changing the sensing node every slot allows a better behaviour of the network as regards the case in wich the sensing is committed to a single node for all the time.

Each node acts indipendently to send its DATA to the BS always at the maximum power because there is no clustering. In this way each node spends more energy for transmissions; moreover when the node causes interference to the primary it does that at an high power level.

Chapter 6

Performance Evaluation

6.1 Simulation Environment

Performance evaluation of the Clustered Model mentioned in previous chapter was carried out by computer simulation in the framework of Omnet++ version 3.4b2 simulator [17], in particolar by using Mobility Frame work package under Linux operatng system. The simulator describes an ad hoc network with a parameterizable number of hosts. Each host in the network is an Omnet++ compound module which encapsulates the following simple modules:

1. Application Module
2. Network Module
3. Route Module
4. Nic Module composed of Mac Module and Physical Module

In the original Mobility Framework structure the routing module was not present and it was created to easier introduce sensing and clustering operations which in real network are managed in Nic Module.

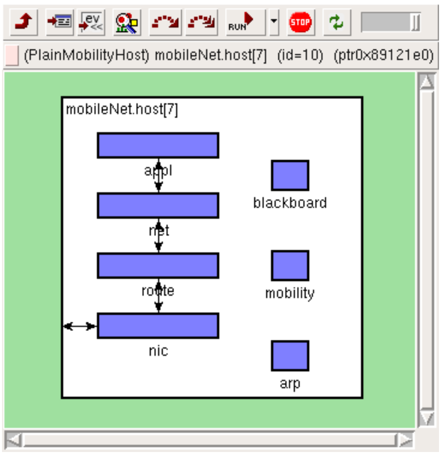

Figure 6.1 Implemented Mobile Node Architecture

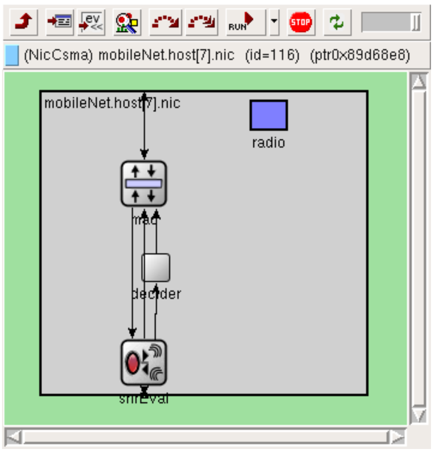

Figure 6.2 Nic Layer

We now analize each layer starting with the network environment.
We consider a playground of 1000x1000 meters, in which a variable number of host, from 20 to 50 nodes, exchanges control and data traffic for a simulation time varing from 5 to 15 hours. A primary transmitter operates in the area with a certain percentage of activity PA. The values are reported in Table 6.1.

Playground Size	1000x1000 meters
Number of Hosts	20; 30; 40; 50
Primary Transmitted Power	126mW
Primary PA	75%
Simulation Time	5 to 15 hours

Table 6.1 Network Environment

The physical and mac module are carried on in the block called Nic (Network Interface Card). The physical module uses some parameters described in [18] like the carrier frequency and the header length, while AWGN power is calculated over the bandwidth of interest. It is created using two additional sub-modules: SnrEval and SnrDecider.
The SnrEval module simulates a transmission delay for all received messages and calculates the SNR information. In this submodule the energy evaluation is introduced.
The SnrDecider module processes the messages coming from the channel. The messages coming from upper layers bypass the SnrDecider module and are directly handed to the SnrEval module.
In Table 6.2 are shown the fixed values for the Physical module.

The MAC module is based on Carrier Sensing Multiple Access (CSMA).
Sensing is done using a detection for radio states. So if the channel is free, messages are sent; instead if the channel is busy the messages

Carrier Frequency	3.5 GHz
Bandwidth	20 MHz
Max Transmitted Power	10 mW
Intra-Cluster Transmitted Power	0.05; 0.2; 0.6 mW
Thermal Noise	-101 dBm
Threshold Level	4.6 dB
Header Length	64 bit

Table 6.2 Physical Module

are bufferized and put in queue. the bitrate and the header length used are the same seen for 802.15.4. We can summerized this parameters in Table 6.3.

Bitrate	250 kb/s
Header Length	104 bit
Inter-arrival Time	0.006
Queue Length	1 MB

Table 6.3 Mac Module

The routing is the core of entire project. Here are elaborated the sensing and clustering information. In Table 6.4 are showed important parameters for the module.

Sensing and Clustering Message Size	16 bit
ε	0; 0.25; 0.5; 0.75; 1
ρ	$1-\varepsilon$

Table 6.4 Sensing and Clustering Module

The network module is the same of traditional Mobility Framework. Only the header length has been changed as shown in Table 6.5.

Header Length	64 bit

Table 6.5 Network Module

The application module is responsible for the traffic generation. The traffic is generated using exponential function to select timers for new connections (connection interarrival mean period) and to create the number of packets (packet average). So are created connections that enable a node to transmit. In Table 6.6 we summerize the parameter for the application module.

Data Payload	748 bit
Header Length	64 bit
Packet Average	1
Network Connection Interarrival Mean Period	0.25 0.125; 0.083; 0.0625 s

Table 6.6 Application Module

6.2 Simulation Results an Discussion

In this work three sets of simulations have been object of study. Each set allowed to analize the cognitive network's behaviour in function of some parameter. In the following we will show and discuss the observed results.

6.2.1 Clustered Model

In this section we compare performances of Clustered Model with the Basic one in function of the number of nodes and of the DATA traffic, with other parameters fixed. A growing number of nodes leads to more connections per second in the network. We have settled the values of the weights ϵ and ρ, used to calculate the Total Weight Λ in the clusterization process, and the cluster range. Details are described in Table 6.7.

Simulation Time	5 hours
Number of Nodes	20; 30; 40; 50
Network Connections per second	4; 8; 12; 16
ϵ	0.7
ρ	0.3
Cluster Range	200 meters

Table 6.7 First Set of Simulations.

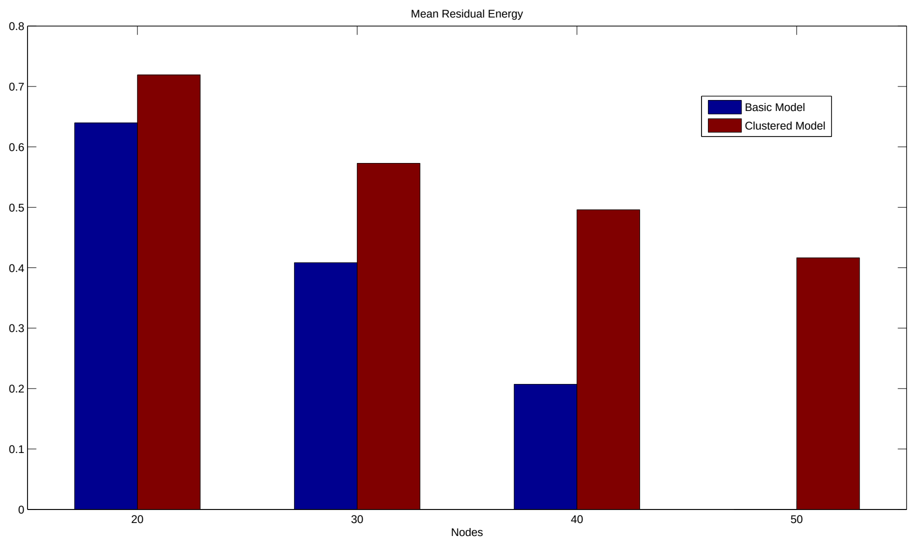

Figure 6.3 Reduction of Energy Consumption for a CR Node in the Clustered Model (in percentage).

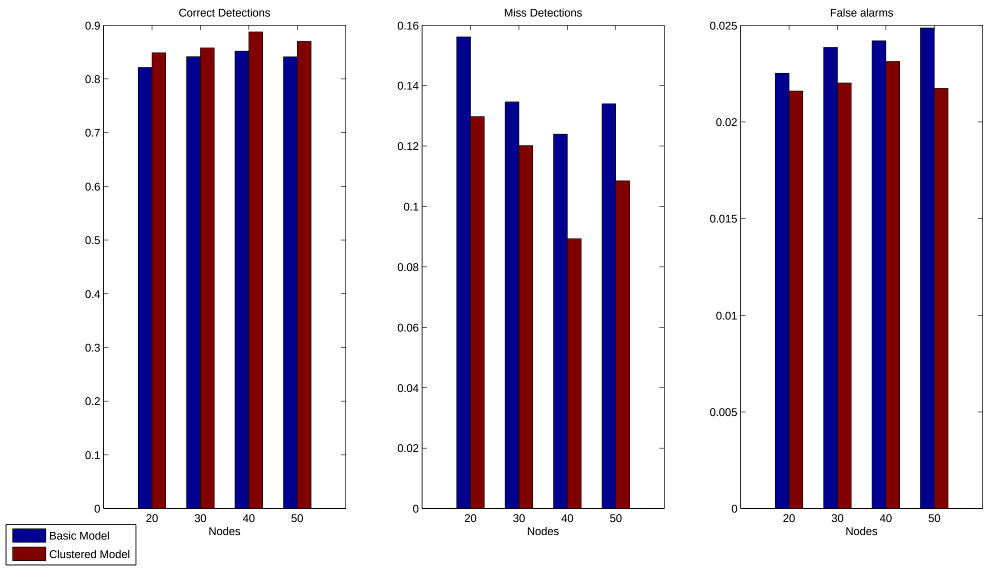

Figure 6.4 Advantages of Majority Fusion Rule for Primary Activity Detection in Clustered Model.

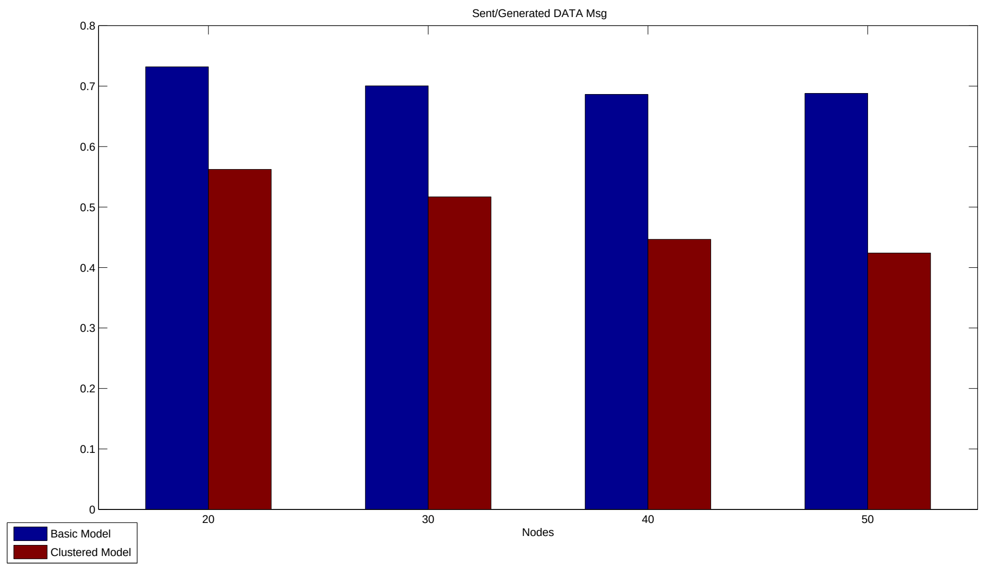

Figure 6.5 Percentage of Total Sent DATA Messages on Total Generated DATA Message in the two Models.

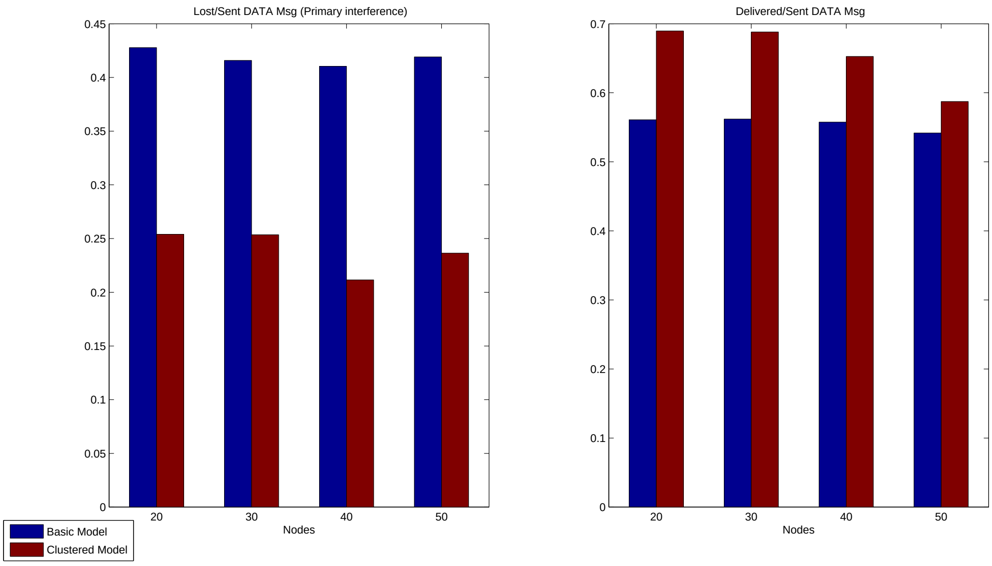

Figure 6.6 Percentage of DATA Lost as Measure of Interference and of DATA Delivered in the two Models.

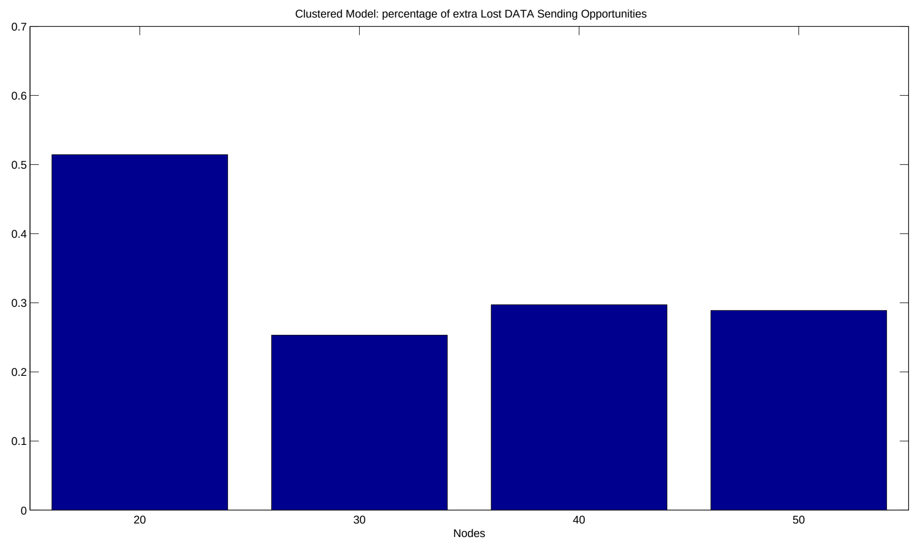

Figure 6.7 Preventive Behaviour of CHs Leads to Higher Lost Opportunities for Sending DATA (extra-percentage as regards the Basic Model).

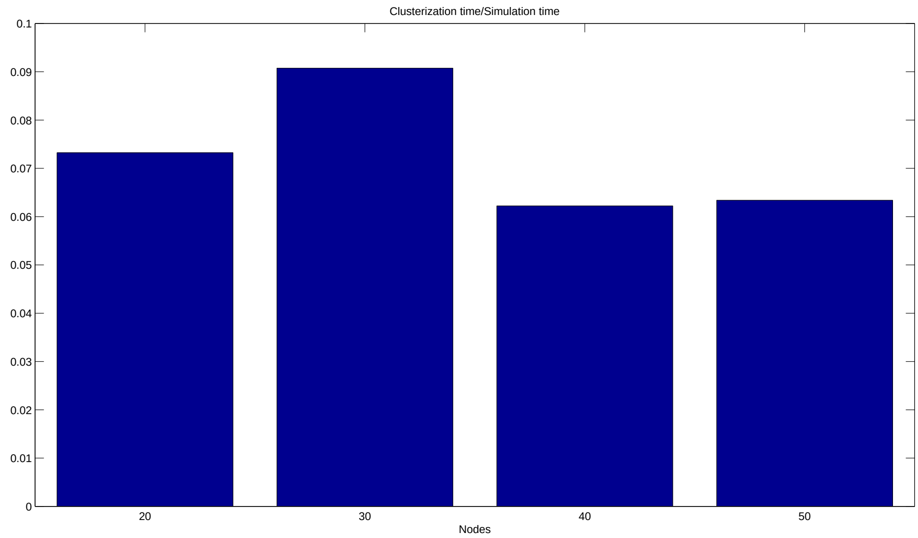

Figure 6.8 Percentage of Network Life-Time Spent for Clusterization.

The Clustered Model, after 5 hours simulation, achieves optimal results as regards the life-time of the CR nodes, overall increasing the popolation of the network (see Figure 6.3). This thanks to the better detection approach (see Figure 6.4).

The majority fusion rule is applied to the set of decision taken by nodes reliable with weight $\rho = 0.3$. In spite of a not high ρ, detection skill is better; the most important result is the drastic reduction of P_{miss} that leads to a reduction of interference toward the primary activity.

From Figure 6.5 we can see that the Clustered Model sends less DATA packets in the air: in one hand because the detection system works better and this can be seen in Figure 6.6 where the Basic Model losts much more DATA packets interfered by primary transmissions, in the other hand because the CHs acts preventively stopping transmissions just they sense the channel BUSY. This last behaviour avoids inter-

ference if the CH decides correctly, but avoids opportunities of transmitting DATA if the channel is effectively IDLE and the CH decides wrong (see Figure 6.7).
During Training and Clustering States DATA traffic is still, but time spent in these operations is an acceptable percentage of the network life-time (see Figure 6.8).

6.2.2 Weights Balancing

This section is dedicated to research the optimal distribution of weights ϵ and ρ (that determine the relevance of residual energy and reliability respectively in a CR node when it competes to become CH) for cognitive network performances.
Details on parameters are showed in Table 6.8.

Simulation Time	20 hours
Number of Nodes	50
Network Connections per second	16
ϵ	0; 0.25; 0.5; 0.75; 1
ρ	1 - ϵ
Cluster Range	200 meters

Table 6.8 Second Set of Simulations.

The formula of the Total Weight was

$$\Lambda = \epsilon * \frac{E_{residual}}{E_{total}} + \rho * R_{eliability} \tag{6.1}$$

Before simulation results, the expectations were to see for high ϵ a longer network life-time, due to a more uniform consumption of energy of the nodes through energy-efficient clusterizations, against less reliability of the CHs and consequently more interference toward the

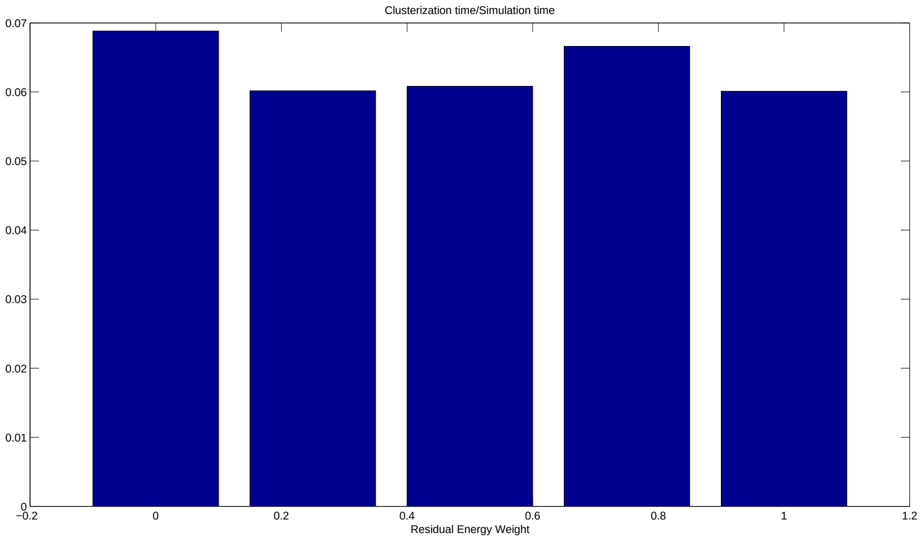

Figure 6.9 Mean Residual Energy in the CR Node function of ϵ (in percentage).

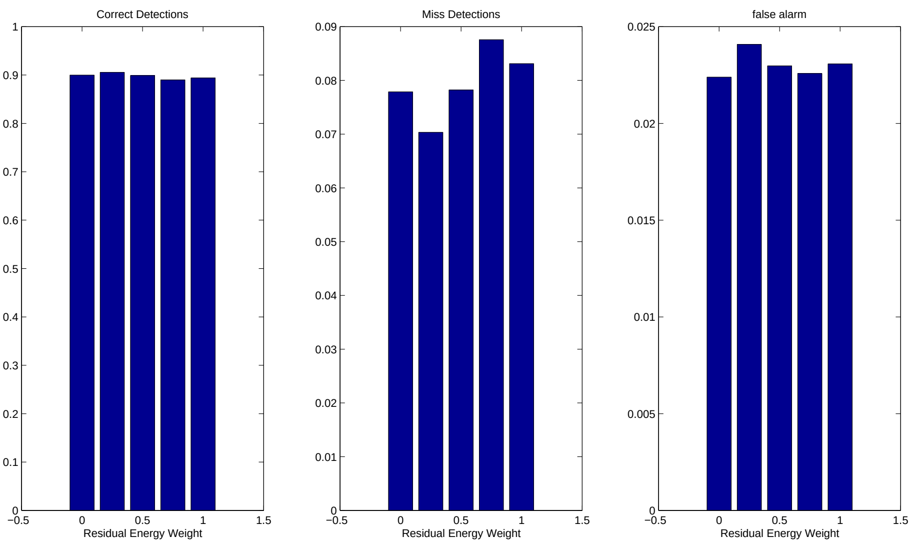

Figure 6.10 Detection Behaviour function of ϵ.

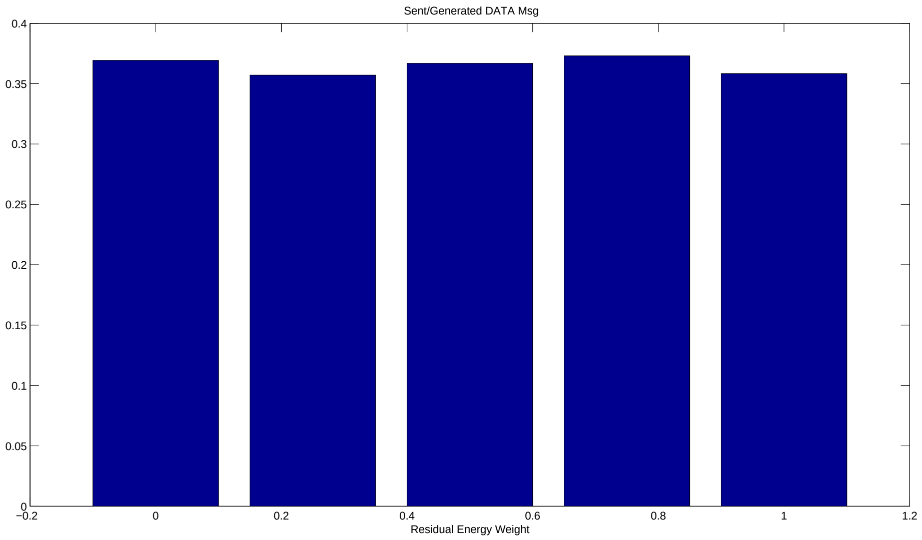

Figure 6.11 Sent DATA Message on Generated DATA Message function of ϵ.

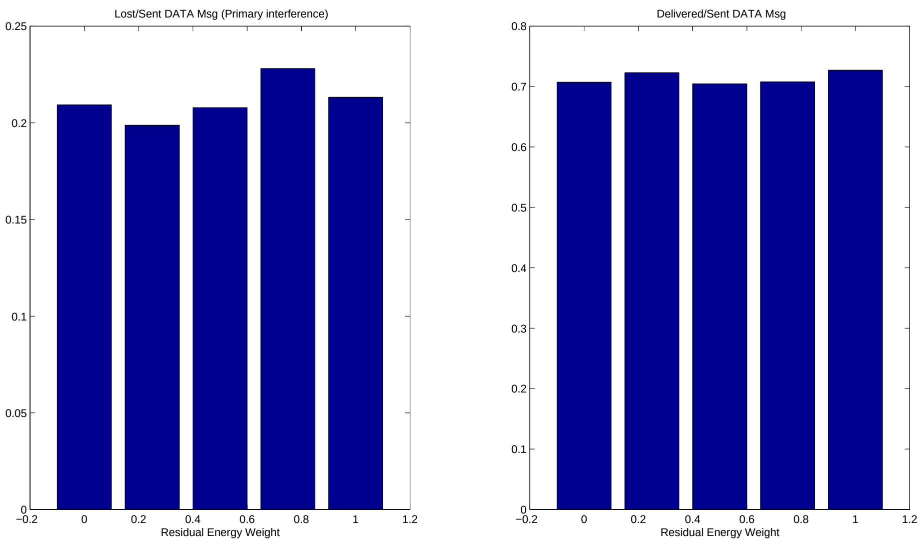

Figure 6.12 Lost DATA Message by Primary interference and Delivered DATA Message function of ϵ.

primary users; instead for low ϵ the expectations were to see a shorter network-life against a better behaviour of the secondary network toward the primary one, thanks to reliability-efficient clusterizations. Results show that it is not so clear that a trade off to exist. It seems that also from an energetic point of view the network behaves better with high value of ρ and more reliable CHs (see Figure 6.9. This can be explained with the fact that, in absolute, in this conditions, less DATA packets are sent in the air, leading in part to less interference but in part also to less delivered DATA message (see Figure 6.12). It seems a good choice to give more relevance to the reliability-weight ρ, but in general there are not so great differences as expected and this aspect sould be studied more deply in next future.

6.2.3 Clusterization Range

This section is dedicated to the research of the best cluster-range and consequently the intra-cluster transmitting power used by CR nodes. Details on parameters are showed in Table 6.9.

Simulation Time	20 hours
Number of Nodes	50
Network Connections per second	16
ϵ	0.7
ρ	1 - ϵ
Max Transmitted Power	10 mW
Intra-Cluster Transmitted Power	0; 0.05; 0.2; 0.6; 10 mW
Cluster Range	0; 100; 200; 350; 1500 meters

Table 6.9 Third Set of Simulations.

All the results would lead to say that the best choice is to reduce at the minimum the possible cluster-range, possibly to the extreme case

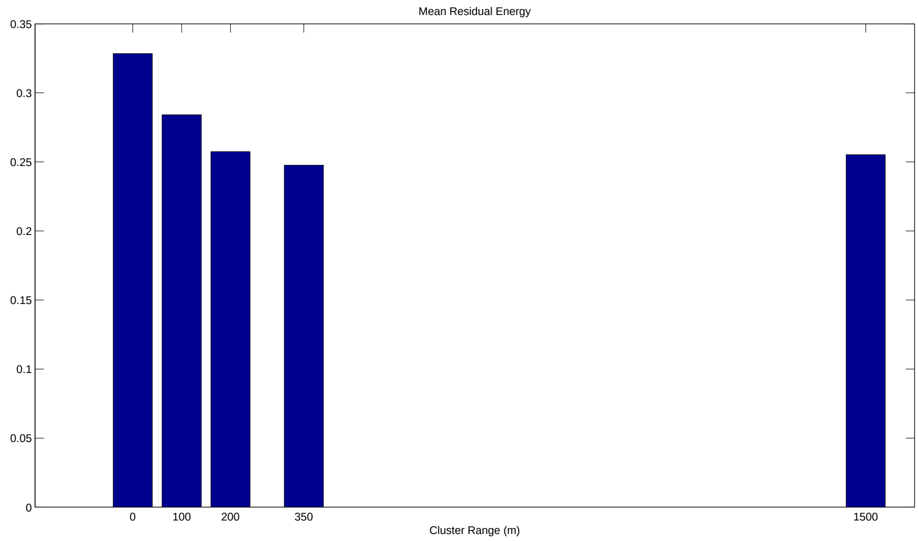

Figure 6.13 Mean Residual Energy in the CR Node function of Cluster-Range (in percentage).

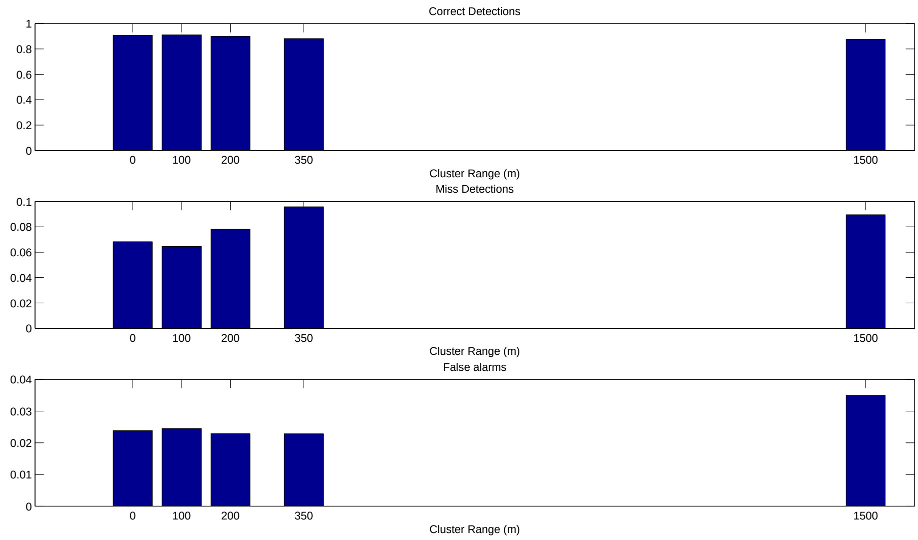

Figure 6.14 Detection Behaviour function of Cluster-Range.

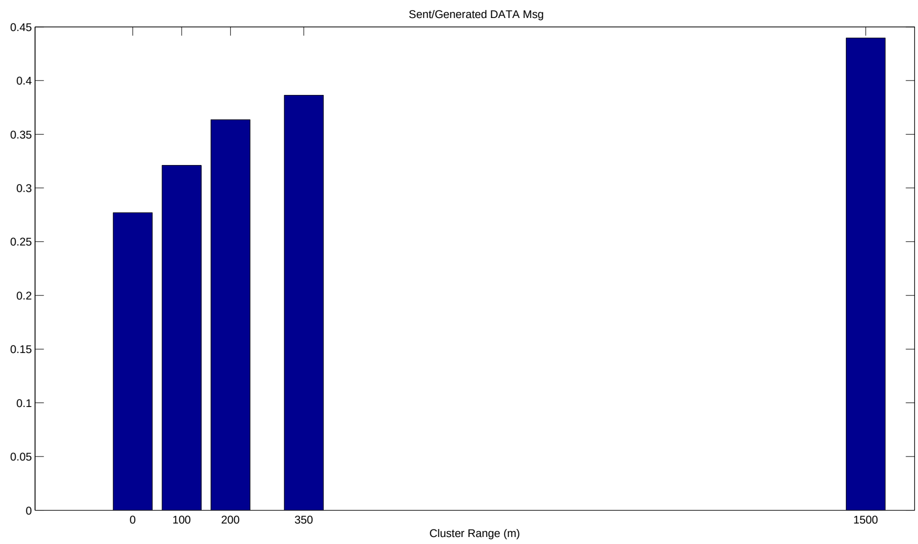

Figure 6.15 Sent DATA Message on Generated DATA Message function of Cluster-Range.

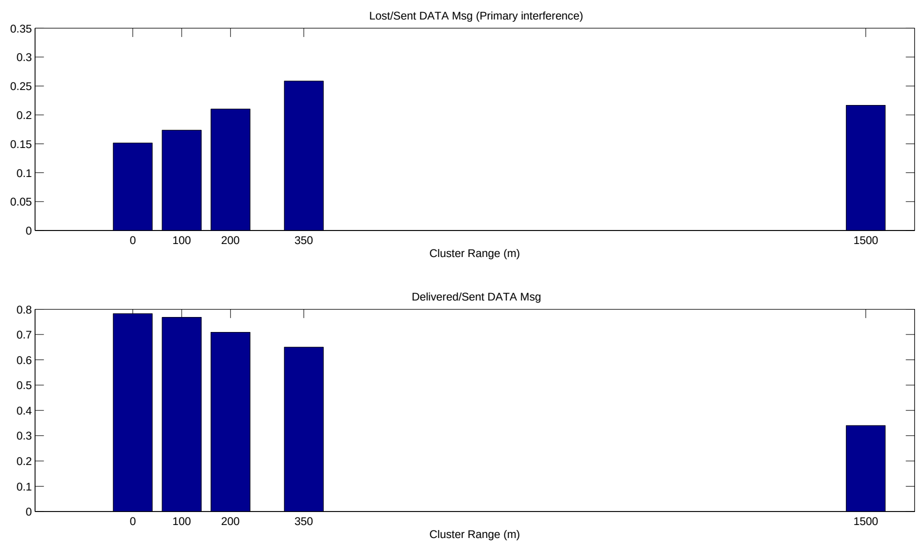

Figure 6.16 Lost DATA Message by Primary interference and Delivered DATA Message function of Cluster-Range.

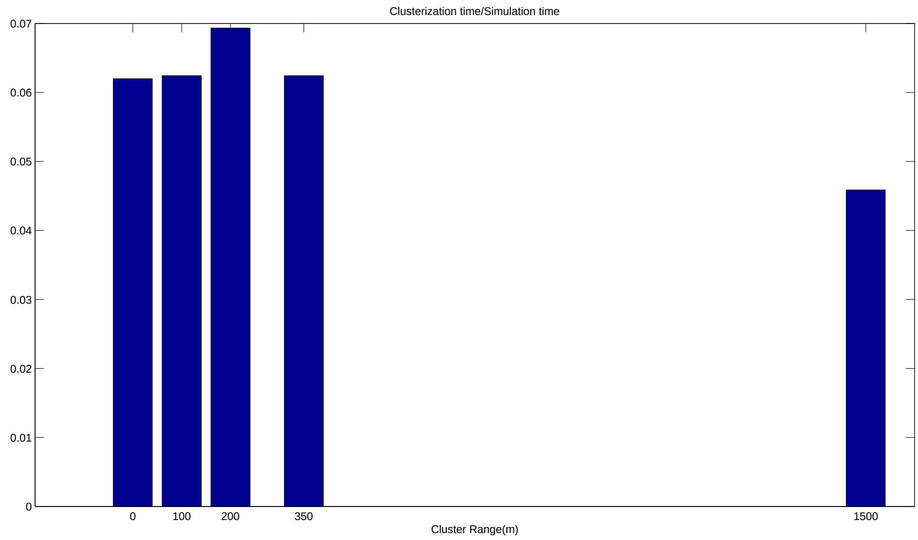

Figure 6.17 Percentage of Network Life-Time Spent for Clusterization function of Cluster-Range.

of no clusterization, but in the two extreme cases of having no cluster or a single cluster, all the CR nodes transmit always at the maximum transmitting power, causing more damage to primary users in case of interference.

In this optical the best choice is to have clusters of 100 meters of radius.

Chapter 7

Conclusions and Future Works

In this work the argument of cooperative spectrum sensing for cognitive radio networks has been studied under the aspects of energy consumption and reliability of detection.
A detection system based on majority fusion rule and on a clustered approach, in wich the nodes that make sensing are the best ones as regards a weighted sum of residual energy and SNR condition toward primary transmissions, proved to have good performances, in particular in Rayleigh fading environments.
Different aspect of this hybrid energy-aware spectrum sensing scheme have been considered and some of them will be object of more careful analysis.
Future researches will regard:

- Choise of the best couple ϵ-ρ to set as regards the clusterization process.
- Deeper analysis for the setting of ΔE and ΔR in the re-clusterization process.
- Comparison with other clustered sensing models seen in literature.
- Study of possibility to introduce mobility in the optical of more flexible mobile-clusters.

Part II

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