Cooperative spectrum sensing towards primary users detection in cognitive radio networks

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Alla fine del mio lavoro, dopo aver trascorso ore e ore davanti al MIO indispensabile MacBook, che mia sorella ha comprato appositamente per me meritandosi il mio primo GRAZIE!!, vorrei riservare un pensiero a tutte le persone che ho avuto vicino nel mio percorso universitario.

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Chapter 1

Introduction

1.1 Wireless Access and Cognition Concept

Traditionally wireless networks are characterized by fixed spectrum assignment policy. With ever increasing demand for frequency spectrum and limited resource availability, FCC decided to make a spectrum policy reform, allowing more and more number of unlicenced users to transmit their signals in licenced bands so as to efficiently utilize the available spectrum. FCC proposed new approaches for efficient spectrum sharing techniques with unlicensed users; one of them is *Cognitive Radios*.
Cognitive Radios [1] is a new paradigm in wireless communication technology wich interacts with real time environment to dinamically change its operating parameters such as transmit power, carrier frequency, modulation to acclimate itself with the environment with the only purpose to take advantage of the available spectrum without causing interference to primary users.

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.

1.2 Motivation and Background

With the incresing number of wireless users, scarcity of electromagnatic spectrum is obvius. Taking this into consideration, the Federal Communications Commission (FCC) published a report [2]. This report recommends rules and regulations for the efficient use of radio spectrum and the ways to improve the existing spectrum usage. In relation to the spectrum utilization this report illustrates that there is significant inefficient spectrum utilization. Most of the allocated channels are not in use most of the time; some are partially occupied while others are heavily used. Measurement of 0-6 GHz spectrum utilization reveals that the lower frequency band is densely populated while at the higher frequencies utilization is not adequate. We call this regions as *Spectrum Holes* or *White space*.

Frequency bands restricted only to licensed users and at any time or location wich are underutilized.

FCC was interested in making these holes or white spaces to be freely used by unlicenced users for the best spectrum utilization because of the growth in 802.11/Wi-Fi unlicenced consumer devices market.
In December 2003, FCC released a report [3] in wich it took an initiative wich allows the use of this underutilized spectrum to unlicenced users to operate in television spectrum in areas where the spectrum is not in use. However, these unlicenced users should not create interference to the licenced user and at times the licenced user wants to transmit its signal the unlicenced user should look for some other free space. This could be achieved by incorporating *Cognitive Radios* to

sense unused spectrum.

1.3 Cognitive Radio

The name *Cognitive Radio* (CR) was originally coined by Joseph Mitola III in an article published in 1999: Mitola's intention 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 device equipped with *Cognition*.

From this definition, two main characteristics of the cognitive radio can be defined:

> *Cognitive capability*: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment, such as temporal and spatial variations, and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.
>
> *Reconfigurability*: Reconfigurability enables the radio to be dynamically programmed according to the radio environ-

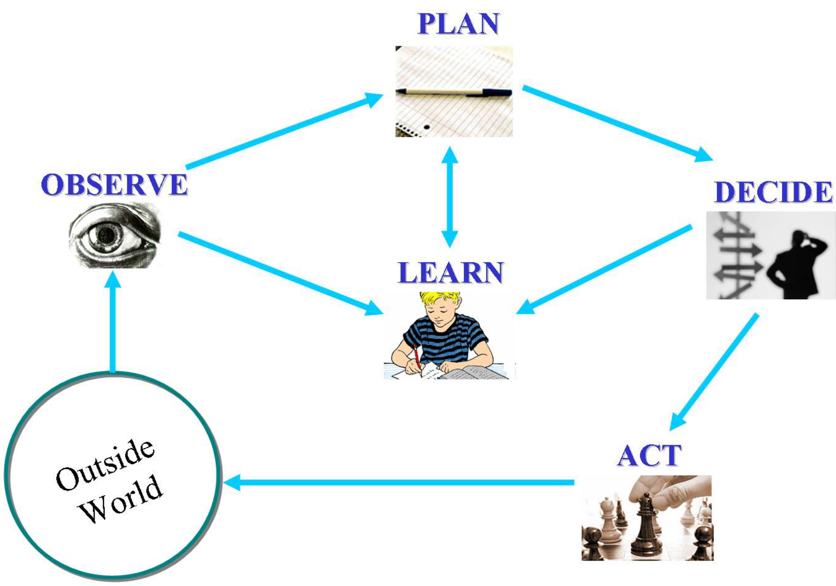

Figure 1.1 Phases composing the cognitive cycle.

ment.

These features can be provided by an extremely efficient *Software Defined Radio* (SDR) embedded in the device [4].
The *Federal Communication Commission* (FCC) has recognized the potential of CR devices in order to enhance secondary spectrum markets. 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*.

While Ideal CR devices process an extremely wide range of information, CR devices consider the radio frequency spectrum as the only significant source of information to be processed in a cognitive way, therefore we can refer them as *Spectrum Sensing Cognitive Radio*. A cognitive cycle representation is shown in Figure 1.1.

The main steps of the cognitive cycle as shown in Figure 1.1 are the follows:

1. Spectrum sensing: A cognitive radio monitors the available spectrum bands and detects the spectrum holes.
2. Spectrum analysis: The charateristics of the spectrum holes that are detected through spectrum sensing are estimated.
3. Spectrum decision: A cognitive radio determines the data rate, the transmission mode, and the bandwidth of the transmission. Then, the appropriate spectrum band is chosen according to the spectrum charateristics and user requirements.

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 by *cooperation* among different service providers. *Cooperation* between cognitive nodes (forming a cognitive network) can improve the sensing procedure and simplify the hardware complexity of the single CR device.

One of the key issues in the CR framework remains the way the *sensing* phase is implemented. Sensing is crucial to radio cognition. Different solutions like energy detection, matched filter and energy detector have been suggested, but a general solution doesn't seem to exist, given the wide range of application scenarios.

1.4 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 Omnet++ simulator.
Chapter 5 is devoted to the introduction of novel *Cooperative Spectrum Sensing* technique for primary users detection capable of improving wireless coexistence performance and therefore decreasing interference.
Chapter 6 discusses the advantages, in terms of throughput, ability in primary detection and energy efficiency deriving from the introduction of different cooperative mechanisms.

Chapter 2

Spectrum Sensing

2.1 Chapter overview

The basic idea for the implementation of Cognitive Radio is to employ a hierarchical model, where primary (licenced) and secondary (unlicenced) users coexist in the same frequency spectrum. Primary users have privileged access to the common channel and can dispose of it according to traffic and quality of service needs. Primary users are expected to be oblivious to the presence of the secondary terminals. Therefore, secondary terminals aim at exploiting the idle periods of primary, usually referred to as spectral holes. The main challenges towards the implementation of the principle of cognitive radio appear to be:

> *Primary activity detection at the secondary nodes (Spectrum Sensing)*: secondary users need to monitor the available spectrum in order to be able to detect spectral holes. A typical way to address the problem is to look for primary transmissions by using a signal detector.
>
> *Transmission opportunity exploitation*: once a spectral hole has been identified, secondary users need to exploit the trans-

mission opportunity so as to satisfy two conflicting objectives:

- making their activity transparent to the primary users;
- maximize their own performance.

Primary activity detection can greatly benefit from cooperation among different terminals as illustrated in Chapter 3.

2.2 Signal Processing Techniques for Spectrum Sensing

Spectrum sensing (SS) is the procedure that a cognitive radio user monitors the available spectrum bands, captures their information, reliably detects the spectrum holes and then shares the spectrum without harmful interference with other users. It still can be seen as a kind of receiving signal process, because spectrum sensing detects spectrum holes actually by local measurement of input signal spectrum wich is referred to as *local spectrum sensing*. The cognitive users in the network don't have any kind of cooperation. Each CR user will independently detect the channel through continuos *spectrum sensing*, and if a CR user detects the primary user it would vacate the channel without informing the other CR users.
The goal of *spectrum sensing* is to decide between the following two hypothesis:

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

in order to avoid the harmful interference to the primary system.

A typical way to detect the primary user is to look for primary transmissions by using a signal detector. Three different signal processing techniques that are used in the systems are *matched filter*, *energy detector* and *feature detection*. In the next subsections we discuss advantages and disadvantages about them.

2.2.1 Matched Filter

The optimal way for any signal detection is a *matched filter* [5]. 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 signals 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. If X[n] is completely known to the receiver then the optimal detector is:

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

here γ is the detection threshold, then the number of samples required for optimal detection are

$$N = [Q^{-1}(P_D) - Q^{-1}(P_{FD})]^2 (SNR)^{-1} = O(SNR^{-1}), \qquad (2.2)$$

where P_D and P_{FD} are the probabilities of detection and false detection respectively.

The main advantage of *matched filter* is that due to coherency it requires less time to achieve high processing gain since only $O(1/SNR)$ 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.

2.2.2 Energy Detector

One approach to simplify matched filter approach is to perform non-coherent detection through *energy detection* [5].
The structure of an energy detector is shown in Figure 2.1.
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 knowledge 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 if the primary or licensed user is present or not. However, due to non coherent processing $O(1/SNR^2)$ samples are required to meet a probability of detection constraint.
In this case we have:

$$T(Y) = \sum_{n=0}^{N-1} Y^2[n] \lessgtr_{>H_0}^{<H_1} \gamma, \qquad (2.3)$$

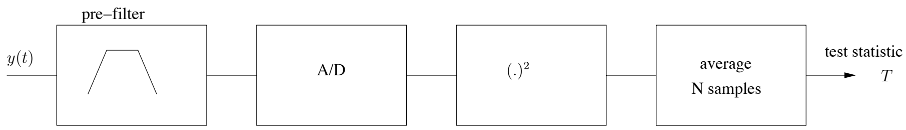

Figure 2.1 Block diagram of an energy detector.

$$N = 2[(Q^{-1}(P_{FA}) - Q^{-1}(P_D)]^2 = O(SNR^{-2}). \tag{2.4}$$

There are several drawbacks in using *energy detection*. First, a threshold used for primary user detection is highly susceptible to unknown 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 secondary 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.

2.2.3 Feature Detection

An alternative method for the detection of primary signals is *Cyclostationary Feature Detection* [5] in which modulated signals are 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 mean and autocorrelation exhibit periodicity. This periodicity is introduced in the signal format at the receiver so as to 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*. The main advantage of this function is that it differentiates the noise from the modulated signal energy. This is due to the fact that noise is a wide-sense stationary signal with no correlation however modulated signals are cyclostationary due to embeddded redundancy of signal periodicity. Analogous to autocorrelation function spectral correlation function (SCF) can be defined as:

$$S_x^a(f) = lim_{T \to \infty} lim_{\Delta t \to \infty} \int_{-\Delta t/2}^{+\Delta t/2} \frac{1}{T} X_T \left(t, f + \frac{\alpha}{2}\right) X_T^* \left(t, f - \frac{\alpha}{2}\right) dt, \tag{2.5}$$

where the finite time Fourier transform is given by:

$$X_T(t, \nu) = \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi\nu u} \, du. \tag{2.6}$$

Spectral correlation function (SCF) is also known as cyclic spectrum. While power spectral density (PSD) is a real valued one dimensional transform, SCF is a complex valued two dimensional transform. The parameter α is called the cycle frequency. If $\alpha = 0$ then SCF gives the PSD of the signal.

Because of the inherent spectral redundancy signal selectivity becomes possible. Analysis of signal in this domain retains its phase and frequency information related to timing parameters of modulated signals. Due to this, overlapping feature in power spectral density are non overlapping feature in cyclic spectrum. Hence different types of modulated signals that have identical power spectral density can have

different cyclic spectrum.
Because of all these properties cyclostationary feature detector can perform better than energy detector in discriminating against noise. However it is computationally complex and requires significantly large observation time.

2.3 Local Spectrum Sensing Limitations

Since cognitive radios are considered lower priority or secondary users of spectrum allocated to a primary user, 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 continous *spectrum sensing*.
Although interference theoretically only happens at receivers, it is difficult for CR to have direct measurement of the communication link between primary trasmitter and receivers.
Consequently because of the complex wireless environment and uncertainess of the locations of primary receivers, the CR must have high sensitivity that outperforms primary user (PU) receivers by a large margin in order to prevent *hidden terminal problem*.
Hidden terminal problem occurs when the cognitive radio is shadowed, in severe multhi-path fading, or inside buildings with high penetration loss while in a close neighbourhood there is a primary user whose is at the marginal reception, due to its more favorable channel conditions. Consequently, the cognitive radio would cause interference to such primary user. Therefore the spectrum sensing performance under low signal-to-noise (SNR) is crucial for above reason.

This results in a complexity detection of primary activity that can be related by the trade off between false alarm probability and missing detection probability: high false alarm probability produces low spectrum utilization; 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 Cognitive Radios

3.1 Chapter overview

In order to improve performance of spectrum sensing the 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 distributed and centralized spectrum sensing are suggested accordingly.
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.

3.2 Cooperation in decentralized cognitive networks

For ad hoc CR network, it is appropriate to take the distributed cooperative SS scheme [6]. 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 the detection decision from other nodes. Because of the imprompt feature of ad hoc CR network, all the nodes should be treated equally for making the 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 $(n + 1)/2 \leq k$, 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. The neighbor of a cognitive radio node means those cognitive radio nodes that can receive its signal directly. It's supposed that a node can directly receive the other node's signal mutually. 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.

3.3 Cooperation in centralized cognitive networks

In this section, we discuss how cooperation could cope with the current issues in spectrum sensing and interference mitigation in cognitive radio networks. The network studied here is infracture based where 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 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. Now, we gives a survey on cooperative spectrum sensing techniques in cognitive radio networks. Generally, the cooperative spectrum sensing techniques can be classified as

- cooperative sensing in cognitive radio;
- cooperative transmission in cognitive radio.

In the following sections, we describe these cooperative spectrum sensing methods.

3.4 Cooperative sensing in cognitive radio

Collaborative spectrum sensing has been proposed and has proved that cooperation between the users improved sensing performance significantly [7]. When the cognitive radio is suffering from shadowing by a high building over the sensing channel, it can not sense the presence of the primary user appropriately due to the low received SNR. Therefore, the cognitive radio access the channel in the presence of the primary user. To address this issue, multiple cognitive radios can be coordinated to perform spectrum sensing cooperatively.

3.4.1 Trivial Solution

Cooperative spectrum sensing is usually performed in two sucessive stages: *sensing* and *reporting*. In the sensing stage, every cognitive user performs spectrum sensing individually. In the reporting stage, all the local sensing observations are reported to a common receiver and the latter will make a final decision on the absence or the presence of the primary user.
The basic idea is to employ distributed detection at the secondary nodes [8]:

1. Each cognitive radio 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 3.1.
This approach is clearly robust to possible unbalance of the channel qualities of different secondary users and shows to achieve a drastic

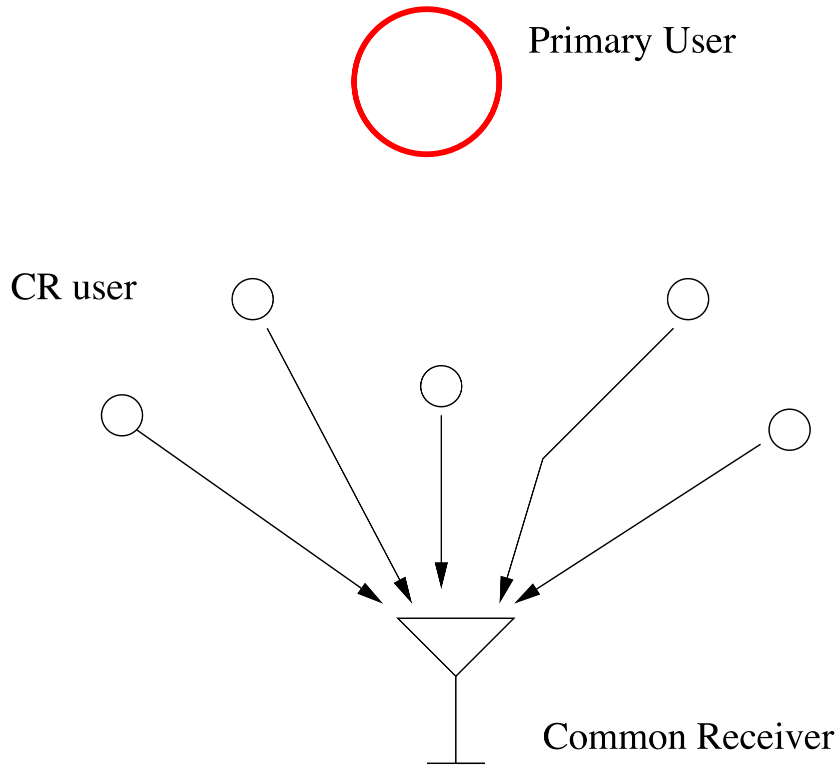

Figure 3.1 Cooperative Spectrum Sensing scheme: Trivial Solution.

improvement of the receiving operating curve.

If the channels between cognitive users are perfect and a generic decision fusion (k out of N rule) is employed at the common receiver, the false alarm probability Q_f and the detection probability Q_d of the cooperative spectrum sensing are given by

$$Q_f = \sum_{j=k}^{N} \sum_{\sum u_i = j} \prod_{i=1}^{N} (P_{f,i})^{u_i} (1 - P_{f,i})^{1-u_i}, \tag{3.1}$$

$$Q_d = \sum_{j=k}^{N} \sum_{\sum u_i = j} \prod_{i=1}^{N} (P_{d,i})^{u_i} (1 - P_{d,i})^{1-u_i}, \tag{3.2}$$

When the decision fusion rule employed at the common receiver becomes an OR rule, the false alarm probability Q_f, the detection probability Q_d and the missing probabilty Q_m of the cooperative spectrum sensing will be written as follows

$$Q_f = 1 - \prod_{i=1}^{N} (1 - P_{f,i}), \tag{3.3}$$

$$Q_d = 1 - \prod_{i=1}^{N} (1 - P_{d,i}), \tag{3.4}$$

and

$$Q_m = 1 - \prod_{i=1}^{N} P_{m,i}, \tag{3.5}$$

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. These are given by

$$P_{f,i} = \mathbf{E}_{\gamma,i}[\text{Prob}\{H_1|H_0\}] = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}, \tag{3.6}$$

$$
\begin{aligned}
P_{d,i} &= \mathbf{E}_{\gamma,i}[\text{Prob}\{H_1|H_1\}] \\
&= e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\bar{\gamma}_i}{\bar{\gamma}_i}\right)^{u-1} \\
&* \left[e^{-\frac{\lambda}{2(1+\bar{\gamma}_i)}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \left(\frac{\lambda\bar{\gamma}_i}{2(1+\bar{\gamma}_i)}\right)^n \right],
\end{aligned}
\tag{3.7}
$$

and

$$
P_{m,i} = 1 - P_{d,i}, \tag{3.8}
$$

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 cognitive radio, $\mathbf{E}_{\gamma,i}[\cdot]$ 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 is the time bandwidth product.

The issue is that in practice the reporting channel between CR node and the Common Receiver may experience fading 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

$$
Q_f = 1 - \prod_{i=1}^{N} \left[(1 - P_{f,i}) \left(1 - P'_{f,i}\right) + P_{f,i} P'_{m,i} \right], \tag{3.9}
$$

$$Q_m = \prod_{i=1}^{N} \left[P_{m,i} \left(1 - P'_{f,i} \right) + \left(1 - P_{m,i} \right) P'_{m,i} \right]. \qquad (3.10)$$

It can be seen that $P'_{f,i} = P'_{m,i}$. For notation brevity, we use $P_{e,i}$ to represent the reporting error probabilty, i.e., $P_{e,i} = P'_{f,i} = P'_{m,i}$. 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 $\bar{Q}_f$.

3.4.2 Cluster-Based Solution

In order to reduce the reporting error probability $P_{e,i}$ and improve the sensing performance, we may also take advantage of multiuser diversity in cooperative spectrum sensing [9].
By taking advantange of the indipendent fading channels, multiuser diversity can be exploited in cooperative spectrum sensing.

Now we consider that the reporting channel experiences Rayleigh fading and propose a cluster-based cooperative spectrum sensing method to improve the sensing performance. Here we make two assumptions:

- the istantaneous channel state information of the reporting channel is available at the cognitive users;
- 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 3.2.
The basic idea is to adopt a cluster-based cooperative spectrum sensing solution that can be summarize through the following steps:

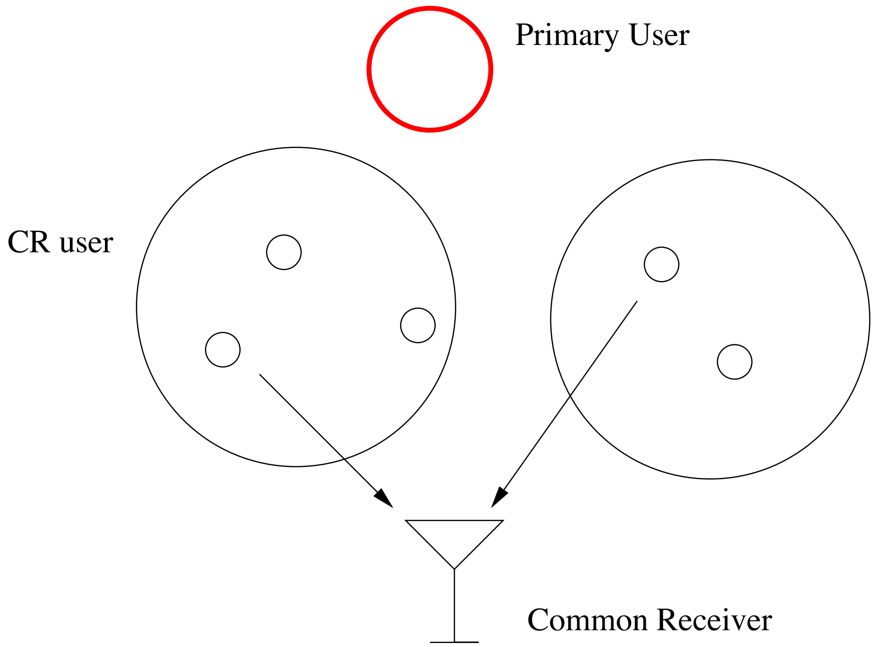

Figure 3.2 Cluster-based cooperative spectrum sensing in cognitive radio systems.

1. All cognitive radios are clustered into a few group according to a clustering algorithm.

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

$$G_{i,j} = \Omega\left(O_{i,j}\right), i = 1, 2, ..., K, j = 1, 2, .., N_i, \tag{3.11}$$

   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

$$B_i = \Phi\left(G_{i,1}, G_{i,2}, ..., G_{i,N_i}\right), i = 1, 2, ..., K. \tag{3.12}$$

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

$$H = \Psi\left(\hat{B}_1, \hat{B}_2, ..., \hat{B}_K\right), \tag{3.13}$$

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, we assume that the primary user is present. Thus the OR-rule in the common receiver is

$$\Psi : H = \begin{cases} 1 & \text{se} \sum_{i=1}^{K} \hat{B}_i \geq 1, \\ 0 & \text{otherwise}. \end{cases} \tag{3.14}$$

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

$$Q_f = 1 - \prod_{i=1}^{K} \left[\left(1 - Q_{f,i}\right) \left(1 - Q_{e,i}\right) + Q_{f,i} Q_{e,i} \right], \tag{3.15}$$

$$Q_m = \prod_{i=1}^{K} \left[Q_{m,i} \left(1 - Q_{e,i}\right) + \left(1 - Q_{m,i}\right) Q_{e,i} \right]. \tag{3.16}$$

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. Now we consider cluster i 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.,

$$\rho_{max,i} = max \left(\rho_{i,1}, \rho_{i,2}, ..., \rho_{i,N_i}\right), \tag{3.17}$$

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

$$f(x) = \frac{N_i}{\bar{\rho}_i} e^{-\frac{x}{\bar{\rho}_i}} \left(1 - e^{-\frac{x}{\bar{\rho}_i}}\right)^{N_i - 1}. \tag{3.18}$$

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

$$Q_{e,i|\rho_{max,i}} = Q\left(\sqrt{2\rho_{max,i}}\right), \tag{3.19}$$

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

$$
\begin{aligned}
Q_{e,i} &= \int_0^\infty Q_{e,i|\rho_{max,i}} f(\rho_{max,i})\, d\rho_{max,i} \\
&= \sum_{m=0}^{N_i-1} \left(\begin{array}{c} N_i - 1 \\ m \end{array} \right) (-1)^{N_i-m-1} \frac{N_i}{2(N_i-m)} \\
&* \left(1 - \sqrt{\frac{\bar{\rho}_i}{N_i - m + \bar{\rho}_i}} \right). \qquad (3.20)
\end{aligned}
$$

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.

An alternative approach to cooperative sensing is interestingly based on cooperative transmission among the secondary users and is discussed in the next section.

3.5 Cooperative Transmission In Cognitive Radio

In another kind of cooperative spectrum sensing the cognitive user with a high signal-to-noise ratio (SNR) is regarded as a relay to forward its observation to the one on the boundary of decidability region of the primary user. This method can effectively reduce the missing probability and detection time.

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 the intended destination, giving rise to two different basic scenarios as explained in the following. Performance advantages achievable from collaboration arises from:

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

3.5.1 Cooperative Transmission Between Secondary Users

In this scenario, a secondary user acts as relay from the transmission of another secondary terminal (source). Since secondary nodes need to continously monitor the channel for possible transmissions by the primary an interestingly proposal is to use cooperative transmission to enhance the sensing process. 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 secondary destination to improve the local detection of the primary user in a scenario where the relay is placed approximately halfway between primary and secondary destination.
Now we consider a two-user cognitive radio network [10]. Cooperative networks 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. We study the effect of the AF cooperation protocol on the spectrum sensing capabilities of cognitive radio network.

Problem Formulation

We assume that 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

$$y = fx + w, \tag{3.21}$$

where the fading coefficient f and the additive noise w are modelled as independent complex Gaussian random variables. Here we assume that there is a centralized controller (capable of both receiver and sending) with which all the cognitive users communicate. We also assume that each user has access to its channel state information. This is facilitated by allowing pilot symbols to be transmitted at regular intervals. An important requirement of a cognitive radio architecture is to detect the presence of primary users as quickly as possible. For this reason cognitive users should continuosly sense the spectrum. Consider a network with two cognitive radio users U_1 and U_2 operating in a fixed TDMA mode for sending data to some common receiver as shown in Figure 3.3.

Suppose that a primary user starts using the band. Then 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 cog-

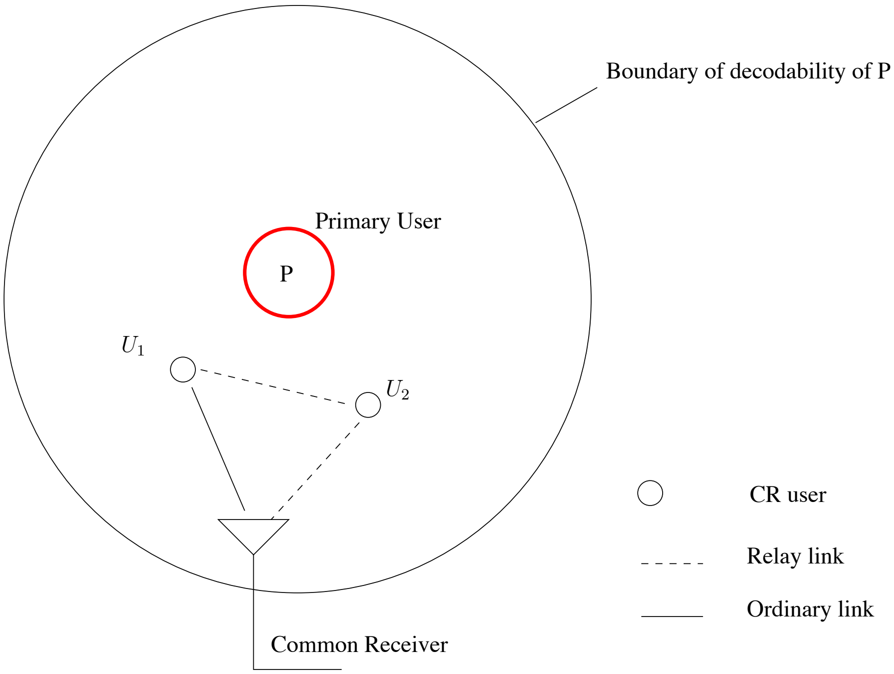

Figure 3.3 Cooperative transmission between secondary users in cognitive network.

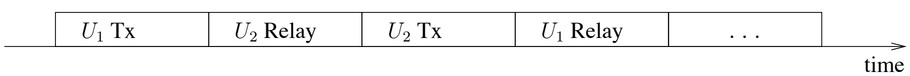

Figure 3.4 Relay protocol used.

nitive 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. We allow the cognitive users, U_1 and U_2, to cooperate, with U_2 acting as a relay for U_1. Figure 3.3 describes a scenario where two cognitive users U_1 and U_2 transmit data to a common receiver in a particular frequency band. Slotted transmission is used wherein U_1 and U_2 transmit in successive slots following the AF protocol as shown in Figure 3.4.

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 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

$$y_2 = \theta h_{p2} + a h_{12} + w_2, \tag{3.22}$$

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,

$$E\left\{|y_2|^2\right\} = PG_{12}, \tag{3.23}$$

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

$$E\left\{|y_2|^2\right\} = \theta^2 P_2 + PG_{12} + 1, \tag{3.24}$$

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 a common cognitive 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

$$\begin{aligned} y_1 &= \sqrt{\beta_1} y_2 h_{12} + \theta h_{p1} + w_1 \\ &= \sqrt{\beta_1} h_{12} \left(\theta h_{p2} + a h_{12} + w_2\right) + \theta h_{p1} + w_1, \end{aligned} \tag{3.25}$$

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. In fact, β_1 is given by

$$\beta_1 = \frac{\tilde{P}}{E\left\{|y_2|^2\right\}} = \frac{\tilde{P}}{\theta^2 P_2 + P G_{12} + 1}. \tag{3.26}$$

After the message component is cancelled, the user U_1 is left with the signal

$$Y = \theta H + W, \tag{3.27}$$

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

$$Y = \theta H + W, \tag{3.28}$$

the detector decides on

$$H_1 : \theta = 1,$$

or

$$H_0 : \theta = 0.$$

This is a very standard detection problem for which there are many choise of detector available as shown in Chapter 2.

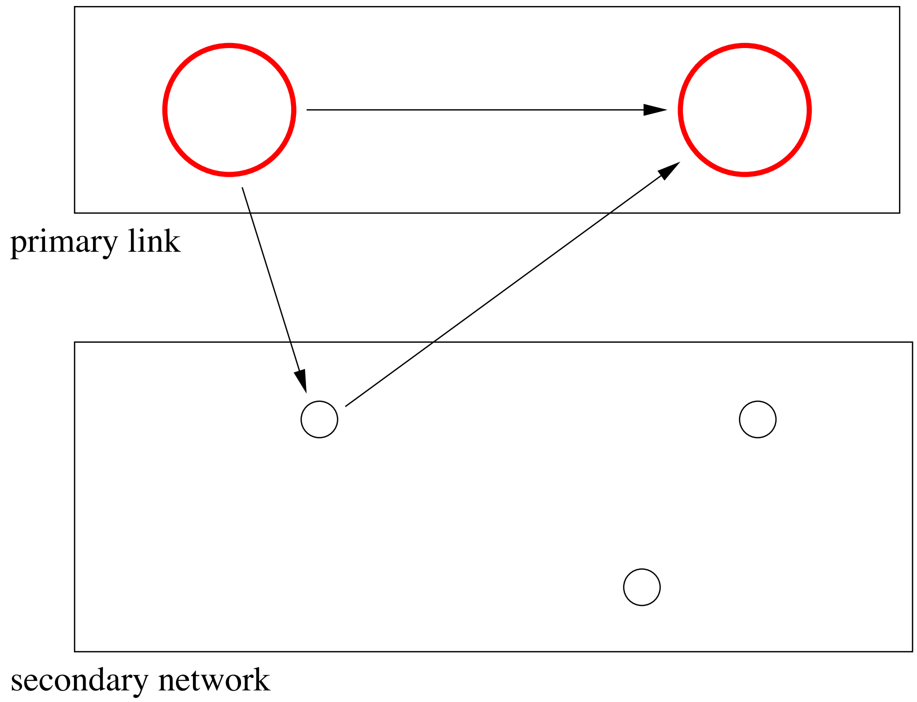

Figure 3.5 Cognitive relay approach for a simple cognitive wireless network with one primary link and a secondary network of three nodes.

3.5.2 Cognitive Relay

A different form of cooperative transmission is the *cognitive relay* [11], where a secondary users has the possibility to relay the traffic of a primary transmitter towards the intended destination as shown in Figure 3.5.

Helping the primary to increase its throughput entails a diminished transmission time of the primary, which leads to more transmission opportunities for the secondary. Therefore, cognitive relaying pursues an enhanced throughput by increasing the probability of transmission opportunities. Now we discuss a simple scenario with one primary and one secondary link where the transmitter may act as relay in or-

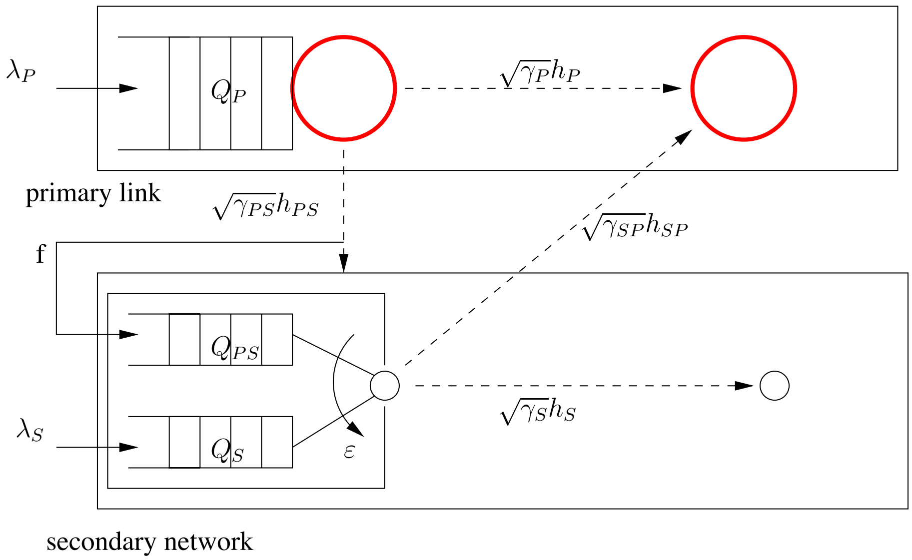

Figure 3.6 A simple cognitive relay model with one primary and one secondary links.

der to show the advantages of cognitive relaying.

System model

Referring to Figure 3.6, both primary and secondary transmitting nodes have an infinite 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 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. 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 $Q_{PS}(t)$, as explained below. 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.

Whenever a primary packet is not correctly received by the 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 secondary transmitter (*cognitive relaying*). Moreover, whenever an idle slot is detected, the secondary transmits a packet from the queque $Q_S(t)$ containing its own packets with scheduling probability ε and from the queque $Q_{PS}(t)$ with complementary probability $1 - \varepsilon$.
We consider that each receiving node sends the respective 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.

Cognitive relaying aims at enhancing the secondary throughput via the increase of transmission opportunities for the secondary. It should be noted that this is achieved by increasing the overall energy consumed by the secondary, since the latter has to deliver not only its traffic but also some packets from the primary. Moreover must be noted that in this scenario secondary users has to know primary transmissions.

Chapter 4

Recever 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 in the received waveform over an observation time window. The object of this chapter is to derive both the probability of detection (P_d) and the probability of false alarm (P_f) in order to describe the receiver operating characteristic (ROC) that will be the input data for our simulation work. These probabilities can be obtained relying on the sampling theorem to approximate the received signal energy and on chi-square statistics of the resulting sum of squared Gaussian random variables.

4.2 System model

Before describing the system model under consideration [7], we first list the main notation that are going to 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.
- Y_T : energy threshold used by the energy detector.
- λ : $\frac{E_s}{N_{02}}$: noncentrality parameter.
- 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.

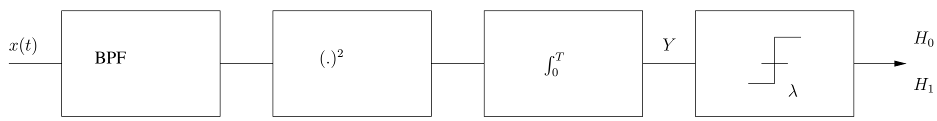

Figure 4.1 Block diagram of an energy detector.

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 [12]

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

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 $(0, T)$

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

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 λ :

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

where λ, 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

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

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

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

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

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

For the same threshold level $Y(t)$, the probability of detection P_d is given by

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

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. If the noncentral chi-square variable has $2TW$ degrees of freedom and noncentrality parameter λ, we can define a modified number of degrees of freedom D and a threshold divisor G given by

$$D = (2TW + \lambda)^2/(2TW + 2\lambda) \quad (4.19)$$

$$G = (2TW + 2\lambda)/(2TW + \lambda). \quad (4.20)$$

Then

$$Prob\left\{\chi^2_{2u}(\lambda) > Y_T\right\} = Prob\left\{\chi^2_D > Y_T/G\right\}. \tag{4.21}$$

4.3 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 [7]:

$$P_d = Pr(Y > Y_T|H_1) = Q_u(\sqrt{2\gamma}, \sqrt{Y_t}), \tag{4.22}$$

$$P_f = Pr(Y > Y_T|H_0) = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}, \tag{4.23}$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot, \cdot)$ are complete and incomplete gamma function respectively and $Q_u(\cdot, \cdot)$ is the generalized Marcum Q-function, defined as

$$Q_u(a, b) = \int_b^{+\infty} \frac{x^u}{a^{u-1}} e^{-\frac{x^2+a^2}{2}} I_{u-1}(ax)\, dx, \tag{4.24}$$

where $I_{u-1}(\cdot)$ is the modified bessel function of $(u-1)-th$ order. The fundamental trade off between $P_m = 1 - P_d$ (probability of missed detection) and P_f has different implications in the contest of dynamic spectrum-sharing. A high P_m would result in missing the presence of primary user with high probability wich in turn increases interference to primary licensee. On the other hand, a high P_f would result in low spectrum utilization since false alarms increase number of missed opportunities (white spaces).

As expected, P_f is independent of γ since under H_0 there is no primary signal present. On the other hand, when h is varying due to shadowing/fading, 4.22 gives probability of detection conditioned on the instantaneous SNR, γ. In this case, average probability of detection (which with an abuse of notation is denoted by P_d) may be derived by averaging 4.22 over fading statistics,

$$P_d = \int_x Q_u(\sqrt{2\gamma}, \sqrt{Y_T}) f_\gamma(x)\, dx, \tag{4.25}$$

where $f_\gamma(x)$ is the probability distribution function (PDF) of SNR under fading. Performance of energy-detector for different values of average SNR and m may be characterized through complementary receiver operating characteristics (ROC) curves (plot of P_m vs P_f). In what follows we study performance under Rayleigh fading.

4.4 Rayleigh fading channels

Under Rayleigh fading channel we can derive the average detection probability [13]. The expression is obteined by averaging the conditional P_d in the AWGN case as given by 4.22 over the SNR fading distribution. Of course, P_f of 4.23 will remain the same under any fading channel since P_f is considered for the case of no signal transmission and such is indipendent of SNR.
If the signal amplitude follows a Rayleigh distribution, then the SNR γ follows an exponential PDF given by

$$f_\gamma = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}\ ,\ \gamma \geq 0. \tag{4.26}$$

The average P_d in this case can be evaluated by sobstituting f_γ in 4.25:

$$\begin{aligned}\bar{P}_d &= e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \left(\frac{\lambda}{2}\right)^n + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{u-1} \\ &* \left[e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{u-2} \frac{1}{n!} \frac{\lambda \bar{\gamma}}{2(1+\bar{\gamma})} \right]. \end{aligned} \tag{4.27}$$

Using 4.26 we can evaluate the distribution function:

$$\begin{aligned} D(\gamma) &= \int_0^{\gamma} \frac{1}{\bar{\gamma}} e^{-\frac{m}{\bar{\gamma}}} \, dm \\ &= \int_0^{\frac{m}{\bar{\gamma}}} e^{-\rho} \, d\rho \\ &= e^{-\rho} \, |_{m/\bar{\gamma}}^{0} \\ &= 1 - e^{-\frac{\gamma}{\bar{\gamma}}} \end{aligned} \tag{4.28}$$

and the inverse function $D(\gamma)^{-1} = -\bar{\gamma} \; log(1-u)$.
Therefore, if u is a random variable uniformly distributed between 0 and 1, the exponential random variable is given by the following non linear transformation:

$$\gamma = -\bar{\gamma} \; log(1-u). \tag{4.29}$$

4.5 Expression for Large Time-Bandwidth Product

When $2TW > 250$, we may use Gaussian approximations to the probability density functions of the test statistic Y under either condition: noise alone, or signal plus noise. The appropriate expressions are found by using a normal variate, with the proper mean and variance, for finding the probability of exceeding the threshold. Let $N(m, \sigma^2)$ indicate a Gaussian variate with mean m and variance σ^2. Y, under the no-signal condition, is the sum of $2TW$ statistically indipendent random variables. The mean value of each variable is simply the variance of the noise variate and is unity. Thus, the mean value is $2TW$. Since each n'_i is a normal variate with mean zero and unit variance, the variance of each n'^2_i is given by

$$var\ n'^2_i = \bar{n'}^4_i - \left(\bar{n'}^2_i\right)^2 = 2. \tag{4.30}$$

Thus, the variance of the sum is $4TW$. Therefore, under the no-signal conditions, Y is distributed as a Gaussian variate $N(2TW, 4TW)$. Then the false alarm probability P_f is given by

$$\begin{aligned} P_f &= \frac{1}{\sqrt{8\pi TW}} \int_{Y_T}^{\infty} e^{\left[-\frac{(x-2TW)^2}{8TW}\right]} dx \\ &= \frac{1}{2} erfc \left[\frac{Y_T - 2TW}{2\sqrt{2}\sqrt{TW}}\right]. \end{aligned} \tag{4.31}$$

In the simulation work we consider a false alarm probability $P_f = 10^{-2}$ and a Time-Bandwidth Product $TW = 1000$. Considering 4.31, we have:

$$Y_T = \sqrt{8TW}\ erfc^{-1}\left[2P_f\right] + 2TW. \tag{4.32}$$

Turning to Y when signal is present, it can be shown that the mean value is $2TW + \lambda$ and the variance is $4(TW + \lambda)$. Thus, we say that Y with signal present is a Gaussian variate $N(2TW+\lambda, 4(TW+\lambda))$. The probability of detection P_d is given by

$$P_d = \frac{1}{2}\ erfc \left[\frac{Y_T - 2TW - \lambda}{2\sqrt{2}\sqrt{TW + \lambda}}\right], \tag{4.33}$$

where λ is the signal-to-noise ratio γ:

$$\gamma = -(\bar{\gamma}\, log(1 - u(0,1))), \tag{4.34}$$

and

$$\bar{\gamma} = \frac{P_t(\lambda/(4\pi r))^2}{noise}, \tag{4.35}$$

is the average SNR.

Chapter 5

Implemantation description

5.1 Application Scenario

A possible scenario that can be considered as an application of cognitive radio technology is a standard for a cognitive radio-based air interference for license-exempt devices operating in a spectrum allocated to the WiMax service.

An istance of cognitive radio user can be descripted as a device that tries to overlay signal with licenced bands in an interference-free manner.

The charateristic of the device used in the simulation are summerized in Table 5.1.

5.2 Basic Sensing Model

The basic sensing model analyzed with an Omnet++ simulation is a simple Cooperative Spectrum Sensing scheme performed in two succesive stages: *sensing* and *reporting*.

User	*Standard*	*Frequency Band*	*Power Level*
PRIMARY USER: WiMax	IEEE 802.16	3.4-3.6 GHZ	126 mW
SECONDARY USER		3.5 GHZ	10 mW

Table 5.1 Simulation parameters for the application scenario

We realized a primary network and a secondary network.
In the primary network, the primary device is a simple module characterized by a fixed position and by a transmission activity factor (FAP, Primary Activity Factor).
The secondary network is composed of a set of sensor dispersed on a field. The nodes in the network are assumed to be in visibility, stationary and all nodes have similar capabilities. One of them is elected to be the *base station*.
In the sensing stage, every cognitive user performs spectrum sensing individually. Every cognitive user performs the sensing one time every (number of nodes * 2) seconds.
In the reporting stage, all the local sensing observations are reported to the base station, so at the base station we have an observation every two seconds. The base station acts as a simple relay node: it forwards the sensing decision, about the absence or the presence of the primary, according to node's sensing evaluation.
Thus an OR-rule is implemented at the common receiver.
The basic idea is to employ distributed detection at the secondary nodes:

1. Each cognitive radio node performs local spectrum sensing measurements independently. Then each node makes its binary decision.

2. All the cognitive users forward their binary decisions to the base station according to the following rule:

   - If the node decides the primary is present, it immediatly sends its decision to the base station and blocks its data traffic.

   - If the node decides the primary is absent, it will send its decision only if it is at least the second time that the sensing performs free chanel result.

3. The base station forwards the absence or presence of the primary user in the observed frequency band acting as a simple relay for the other cognitive users. When a node gets a busy channel information, the base station immediatly blocks its data traffic.

The main difference between a simple host and the base station can be seen in the reporting stage of the sensing information. While the base station is able to speach directly with every cognitive user, a simple host can speach only with the base station. So the base station has to communicate to the other nodes the sensing evaluation performed by each node. The channel sensing protocol implemented for the primary detection can be summerized in the scheme reported in Figure 5.1

5.3 Cooperative Sensing Model

Primary detection is the most importantant requirement for ad-hoc sensor network applications.

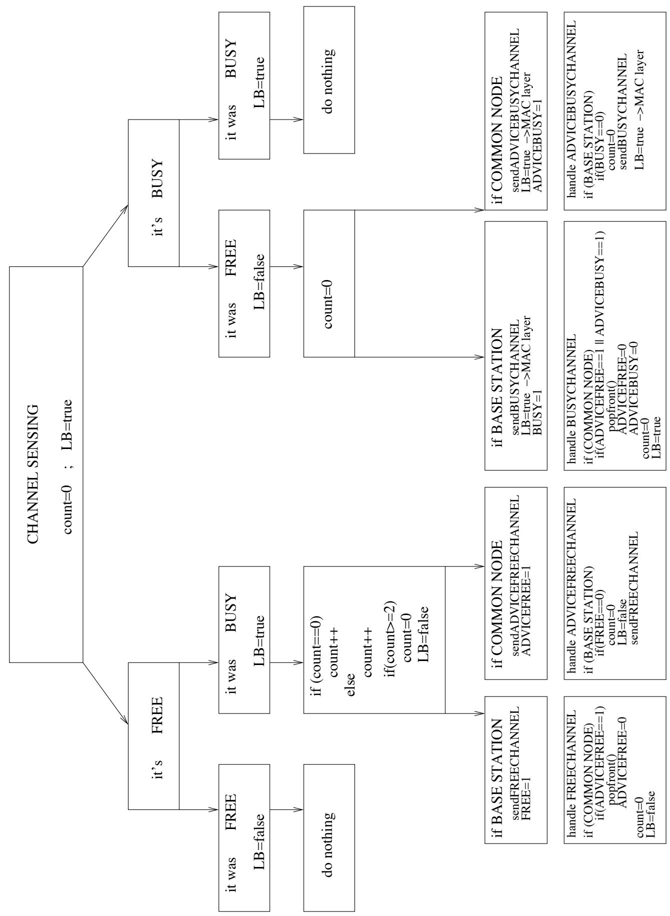

Figure 5.1 Basic channel sensing model.

Based on the investigation of the cooperation between CR nodes, we propose the exchange of spectrum sensing information scheme aims at comprehensive thinking on increasing spectrum utilization, decreasing the interference to primary licensee and also the traffic load in whole network.
Different fusion functions in wireless sensor networks can be used in the common receiver. In order to avoid interference to the primary user, we assume that the cognitive users access the spectrum when the majority of the reported decisions demonstrate that the primary user is absent. Otherwise, we assume that the primary user is present. Thus a MAJORITY-rule is implemented at the common receiver.

In the sensing stage, every cognitive user performs spectrum sensing individually. Every cognitive user performs the sensing one time every two second.
In the reporting stage, all the local sensing observations are reported to the base station.
The base station infers the final decision on the absence or the presence of the primary every two seconds.
We can represent the cooperative spectrum sensing procedure on a time line as shown in Figure 5.2.

The idea is to adopt a cooperative spectrum sensing solution that can be summarized through the following steps:

1. Each cognitive radio node performs local spectrum sensing measurements independently. Then each node makes its binary decision $(1\ or\ 0)$.

2. All the cognitive users forward their binary decisions to the base

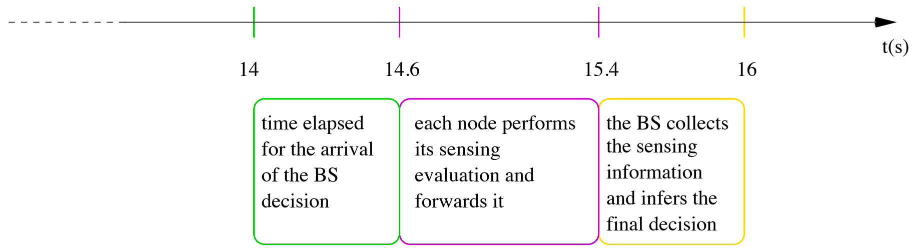

Figure 5.2 Sensing procedure in a cooperative sensing model with a majority decision fusion rule.

station. If a node fels a busy channel, it immediatlyblocks its data traffic.

3. The base station combines all the binary decision available to infer the absence or presence of the primary user in the observed frequency band according to a majority rule. The common receiver takes its decision every two second and communicates it at all. When the nodes receivethis decision they will immediatly set up their state on *busy* or *free* according to the final resolution infered by the base station.

In this case the majority rule consists on the evaluation of the number of nodes that say the primary is present and the other ones. Every two second the base station will communicate the channel state: the channel state will be free if the number of nodes that say the primary is absent is less than the number of nodes that say the primary is present.

The channel sensing protocol can be summerized in the scheme reported in Figure 5.3.

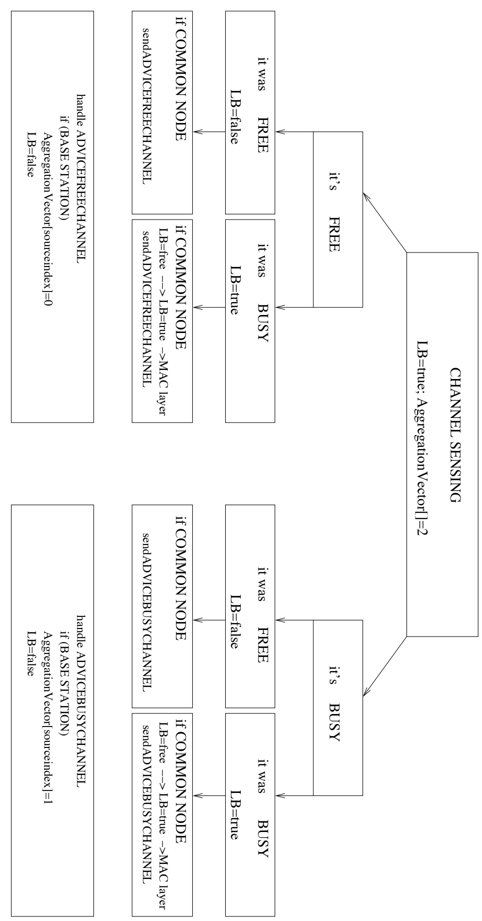

Figure 5.3 Channel sensing model for majority decision fusion rule.

5.4 Cooperative Sensing Model Reliability dependence

Now we investigate some solutions for primary detection that take into account the reliability of each node in detecting the primary user. Reliability is the ability of each node in detecting the presence or the absence of the primary user.
We propose three possible solutions to improve primary detection capability.
The first solution consists of a weighted mean decision fusion rule implemented at the base station.
The second solution consists of a delayed forward of the sensing information implemented in each cognitive node and the decision fusion implemented at base station is a majority rule.
The third solution is a combination of the above two.

For all these scenarios we assume that the reliability is a value included in the interval between zero and one, and we consider a starting reliability value of 0.5. Whenever a node makes a sensing decision in compliance with the decision infered by the base station, its reliability will increase of 0.01. In the opposite case its reliability will decrease of 0.01.
Periodically the reliability is restored to the original value. This period is assumed to be five minutes long.

5.4.1 CSS Weighted mean rule

Based on the fusion function described in the previous section, the idea is to adopt a cooperative spectrum sensing solution that use a weighted mean decision rule taking into account the capability of each

node to detect primary users.
The main steps are the following:

1. Each cognitive radio node performs local spectrum sensing measurements independently. Then each node makes its binary decision (± 1).

2. All the cognitive users forward their binary decisions to the base station and if a node feels that the channel is busy it immediatly blocks its data traffic.

3. The base station weight each binary decision with the reliability of the corresponding node and combines all the binary decisions available to infer the absence or presence of the primary user in the observed frequency band according to a weighted mean rule. The base station adds up this figures and takes the final decision:

   - if the total is a positive number, it says the channel is busy.
   - if the total is a negative number, it says the channel is free.

   The common receiver takes its decision every two second and communicates it at all.

5.4.2 CSS Delay forwarding and majority decision rule

Now the idea is to use the reliability of each node to delay the forwarding of the sensing information that each node produce with the purpose that at the base station arrive only the most dependability sensing information.
The cooperative spectrum sensing solution can be summarized as follow:

1. Each cognitive radio node performs local spectrum sensing measurements independently. Then each node makes its binary decision $(1 \; or \; 0)$.

2. All the cognitive users forward their binary decisions to the base station with a delay that depends by the reliability of the nodes according to the following formula:

$$delay = uniform\left[\frac{0.5}{e^{x+0.1}}, \frac{0.5}{e^{x-0.2}}\right], \tag{5.1}$$

   where x is the reliability of each node.

3. The base station combines all the binary decision available to infer the absence or presence of the primary user in the observed frequency band according to a majority rule. The common receiver takes its decision every two second and communicates it at all.

We can represent the cooperative spectrum sensing procedure on a time line as shown in Figure 5.4.

5.4.3 CSS Delay forwarding and weighted mean decision rule

Now the idea is to combine the above solutions and therefore use the reliability of each node to delay the forwarding of the sensing information that each node produce and to weight the sensing information at the common receiver.
So the cooperative spectrum sensing solution can be summarized as follow:

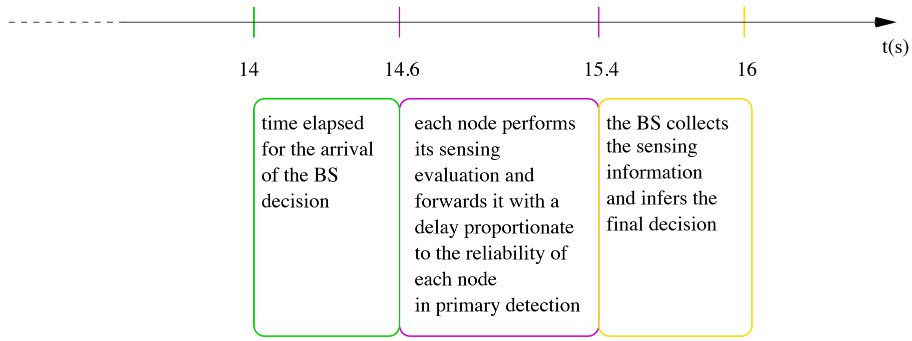

Figure 5.4 Sensing procedure in a cooperative sensing model reliability dependence.

1. Each cognitive radio node performs local spectrum sensing measurements independently. Then each node makes its binary decision (± 1).

2. All the cognitive users forward their binary decisions to the base station with a delay that depends by the reliability of the nodes according to the following formula:

$$delay = uniform\left[\frac{0.5}{e^{x+0.1}}, \frac{0.5}{e^{x-0.2}}\right], \tag{5.2}$$

   where x is the reliability of each node.

3. The base station weight each binary decision with the reliability of the corresponding node and combines all the binary decisions available to infer the absence or presence of the primary user in the observed frequency band according to a weighted mean rule. The base station adds this positive and negative values and takes the final decision:

   - if the total is a positive number, it says the channel is busy.

- if the total is a negative number, it says the channel is free.

The common receiver takes its decision every two second and communicates it at all.
If a node understand that its decision would arrive after the common receiver infers the final decision, it does not forward anymore its sensing information.

Chapter 6

Performance evaluation

6.1 Simulation Environment

Performance evaluation of the proposed cooperative spectrum sensing protocol was carried out by computer simulation in the framework of Omnet++ version 3.4b2 simulator, in particular by using Mobility Frame work package. The simulator describes an ad hoc network with a parameterizable number of hosts. Each host has a defined transmission power. 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

Note that in the original Mobility Framework the routing module was not present.
In the next section we provide key details on each module.

6.1.1 Modules specification

We consider a playground of $1000 * 1000$ meters, in which a variable number of host, from 10 to 50 nodes, exchanges traffic control and data for ona hour. The values are reported in Table 6.1.

Playground size	1000 * 1000 meters
Number of Hosts	Variable 10 to 50
Simulation Time	1 h

Table 6.1 Network Environment

The physical and mac module are carried on in the block called Nic (Network Interface Card). The physical module 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 are bufferized and put in queue. We can summerized the parameters for the Mac Module in Table 6.3.

Carrier Frequency	3.5 GHz
Transmitted Power	10 mW
Thermal Noise	-101 dBm
Threshold Level	4.6 dB
Header Length	64 bit

Table 6.2 Physical Module

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

Table 6.3 Mac Module

The Cooperative Spectrum Sensing is the core of entire project. It is based on different Cooperative Spectrum Sensing tecnique implementation.

The network module is the same of traditional Mobility Framework. Only the header length has been changed as shown in Table 6.4.

Header Length	64 bit

Table 6.4 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 6.5 we summerize the parameter for the application module.

Data Payload	748 bit
Header Length	64 bit
Packet Average	1
Connection Interarrival Mean Period	Variable 0.5 s to 0.16 s

Table 6.5 Application Module

6.2 Simulation Results

Now we examinate and discuss the results obtained for the different cooperative spectrum sensing tecnique introduced in Chapter 5.
All this simulation take into account that the channel of each node is quite good.
The purpose of this work is to find, if it's possible, a cooperative spectrum sensing scheme that will improve primary detection and therefore the coexistence between primary and secondary users in an interference free manner, increasing secondary network' s performances.

To evaluate the performance of the implemented cooperative spectrum sensing schemes descripted in the preovious chapter is useful to compare the correct decisions, the miss detections and false alarms that the secondary network performs in the channel sensing phase to detect the primary user.

These simulations are executed for a secondary network populated by $10, 30$ and 50 cognitive users.
In Figure 6.1 is rapresented the number of correct decision in function of the nodes of the secondary network. As we can see, in the basic sensing scheme (OR decision rule) the number of correct decision is always quite uniform; instead in the other cooperation schemes we have a big improvement of correct decision increasing the number of hosts.
Comparing the different schemes we can say that for a few densely secondary network the OR decision rule appears better then the majority and weighted mean fusion rule, but if we consider a secondary network composed of fifty nodes, the number of correct decision of all the novel schemes proposed exceeds the ones of the basic scheme.

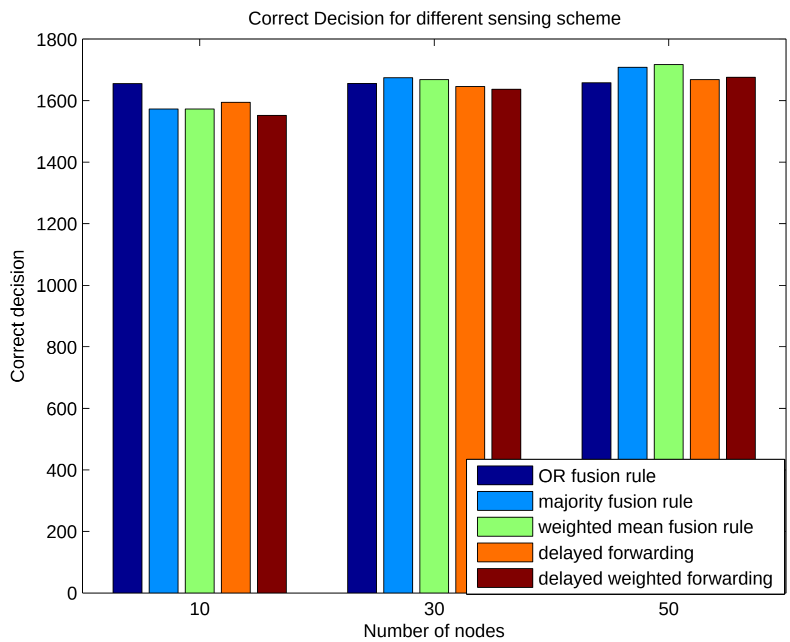

Figure 6.1 Correct decision.

In Figure 6.2 is reported the value of the miss detection: the basic sensing scheme has a uniform value with the increasing of node's number, instead for all the cooparation schemes based on majority fusion rule or weighted mean fusion rule there is a decrease of miss detection, and therefore of the interference, when the number of nodes grows up.
Also in this case we can note that increasing the number of secondary users, majority and weighted mean decision rule are better than OR fusion rule.
Consequently to the interference reduction, we expected an improvement in the percentage of the lost and delivered data messages.
In Figure 6.3 is reported on the x axis the number of secondary users

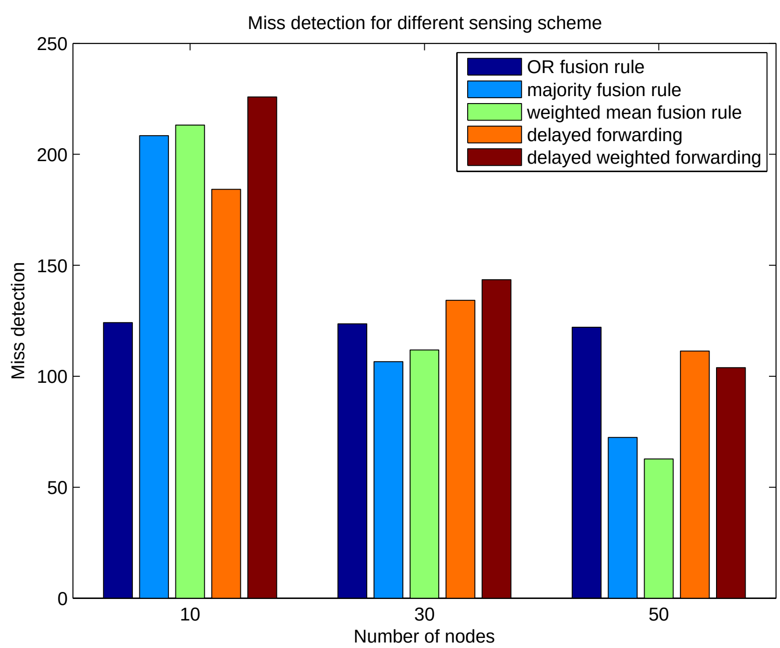

Figure 6.2 Miss detection.

and on the y axis data losted by cognitive radio network. If the secondary network is densely populated all the novel proposed schemes show a decrease in the percentage of data that are sented but not delivered in the network.

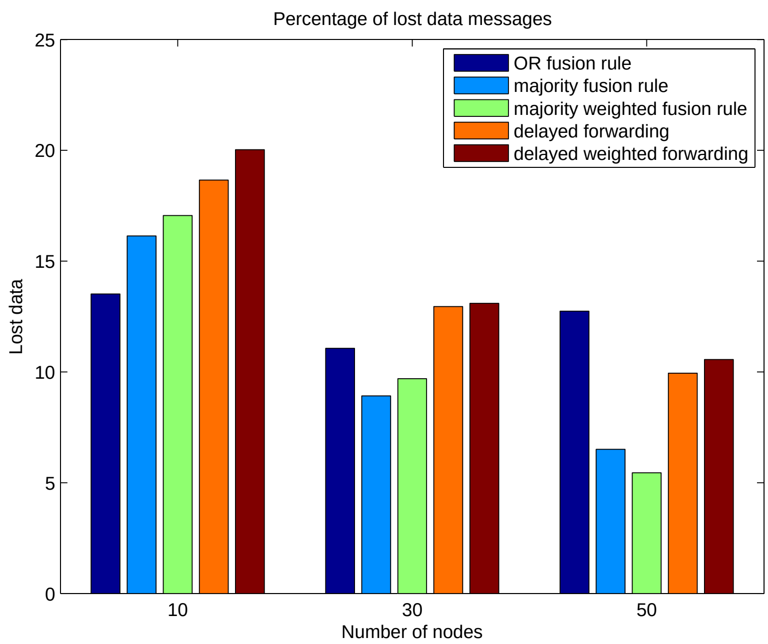

Figure 6.3 Lost Data messages.

In Figure 6.4 are represented the delivered data messages when in the secondary network there are $10, 30$ or 50 users.
Delivered data messages increase with the augmenatation of the secondary users in the network.

In Figure 6.5 we rapresented the false allarm: the pimary is absent but the secondary network decides it is present. In this case there is always an improvement for the cooperative spectrum sensing scheme

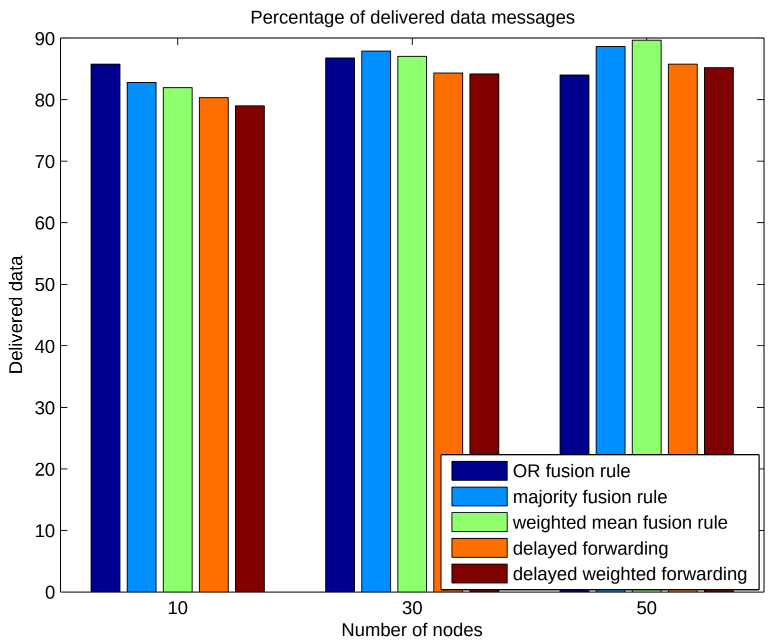

Figure 6.4 Delivered Data messages.

based on majority and weighted mean fusion rule.

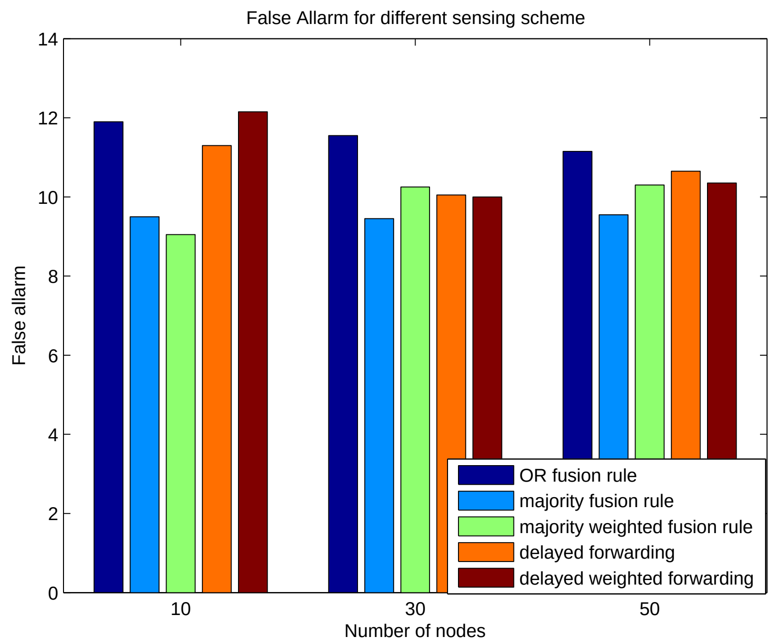

Figure 6.5 False Alarm.

Decreasing the number of false alarm we expect that the transmissions opportunity possibility of transmission of the secondary network will increase; infact as we can see in Figure 6.6 the percentage of the sent data messages exhibits a uniform augmentation.

6.3 Energy consumption

From the reported results we could say that the cooperative spectrum sensing scheme that gives the best performance is the one which implement a weighted mean decision rule. Infact it is the best in terms of correct decision, miss detection and false alarm.

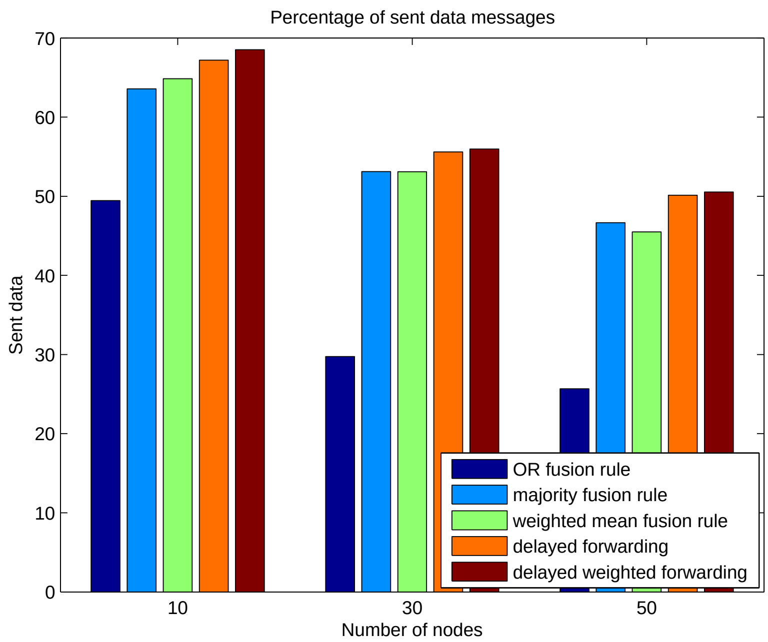

Figure 6.6 Sent Data messages.

Now we want to consider also the system lifetime in terms of mean residual energy for each node in the secondary network at the end of the simulation time.
The energy parameter E is calculated taking in account the Friis formulation for free space transmission and the following model [14]:

$$E_{RX} = E_{Start} + L * (E_{RxBitFixed} + E_{RxBitRate}(R_b)), \tag{6.1}$$

and

$$E_{TX} = E_{Start} + L * (E_{TxBitRate}(R_b) + E_{TxBitProp}(R_b) * d^{\alpha}), \tag{6.2}$$

where L is the length of the packet, $\alpha = 2, d = 1$ and

$$E_{start} = 2,76 * 10^{-5}, \tag{6.3}$$

$$E_{RxBitFixed} = 1,13 * 10^{-7}, \tag{6.4}$$

$$E_{RxBitRate}(R_b) = 2,79 * 10^{-7} * \left(\frac{Bitrate}{10^6}\right), \tag{6.5}$$

$$E_{TxBitRate}(R_b) = 3,25 * 10^{-7} * \left(\frac{PacketRate}{10^6}\right), \tag{6.6}$$

$$E_{TxBitProp}(R_b) = 1.25 * 10^{-12} * \left(\frac{PacketRate}{10^6}\right). \tag{6.7}$$

This parameter is update every time a node makes sensing or sent/receive messages.

The energy state of the nodes at the end of 1 h of simulation is reported in Figure 6.7 for different dnsity of population of the secondary network.

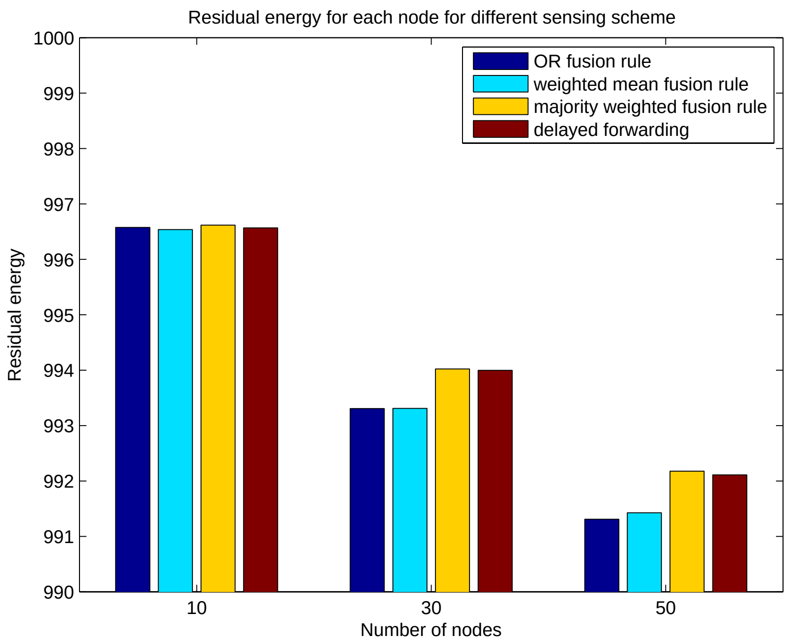

Figure 6.7 Residual energy for each node after 1h simulation.

Two groups seems to appear: the first group is composed by the schemes that proposed the majority and the weighted mean decision rules at the common receiver; the second group is rapresented by the delay forwarding schemes. When the network is few populated there are not difference in the energy consumption between the two groups. A difference in the energy consumption can be seen when the number of secondary users grows up.

In the schemes where is applyed a delayed forwarding of the sensing information there is a lower energy consumption due to a lower amount of the sensing messages sent as it is shown in Figure 6.8.

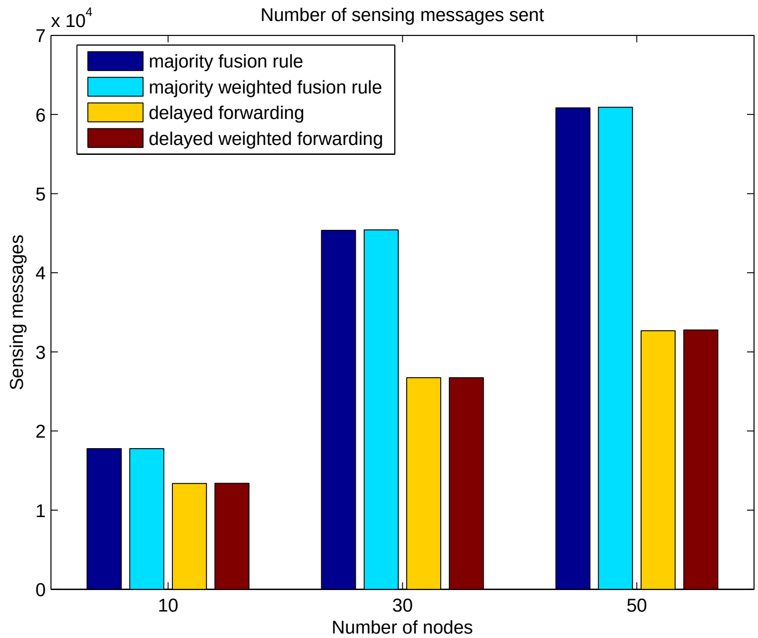

Figure 6.8 Sent Sensing messages.

6.4 Channel variation

Another aspect to take into account is what happen when the channel is not good for all nodes.
We repeated the same simulation and the results are reported in Figure 6.9, 6.10, 6.11.
While the false alarm have still an improvement, the interference with the primary increases a lot. This is obvious because if many hosts have a bad channel, they make a lot of mistake in primary detection and the final decision performed by the base station will be wrong. We

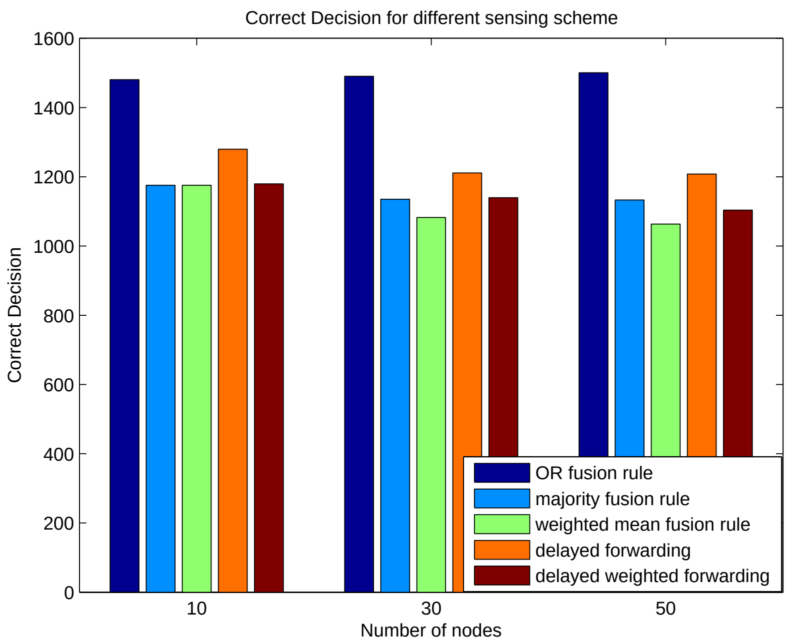

Figure 6.9 Correct decision.

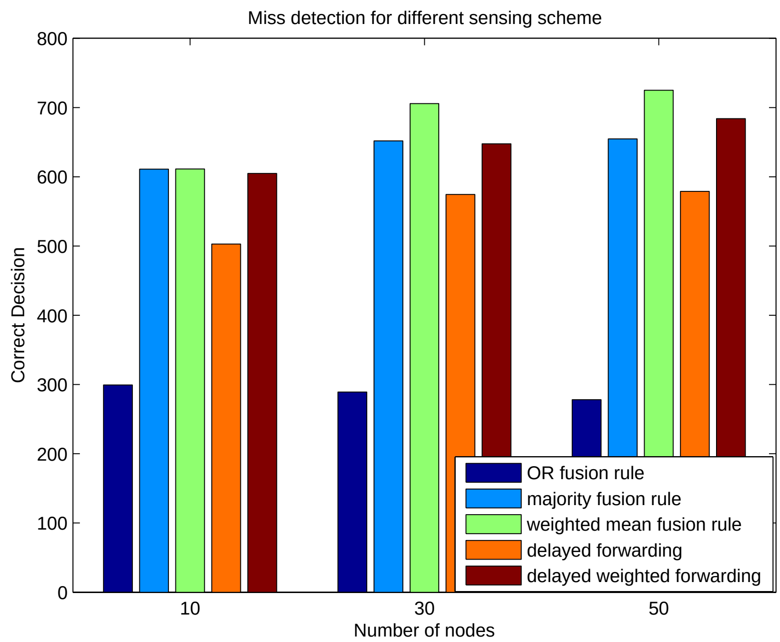

Figure 6.10 Miss Detection.

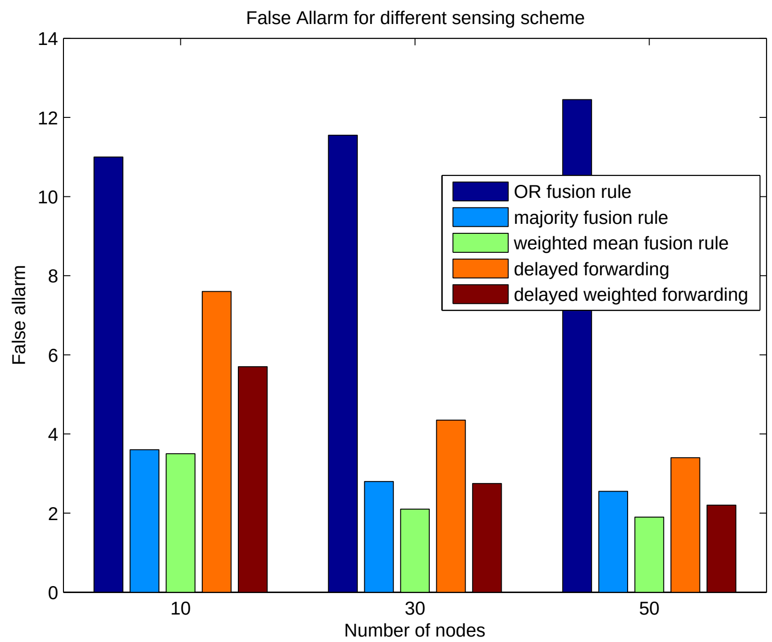

Figure 6.11 False Alarm.

can note that when the channel is not good, the delayed forwarding scheme present an improvement compared with the simple majority fusion rule.

6.5 Conclusion and Future Work

In this thesis we have discussed about cognitive radio and the ooperative spectrum sensing techniques that avoid to cause interference to primary users.

The first consideration to do is that if the nodes have a good channel, majority and weighted mean decision rule gives better performance of an OR rule.
We can also observed that among all the novel fusion rule proposed in this work the delayed schemes seems to be a little worse then non delayed schemes, but this result is probably due to the CSMA protocol implemented in the Mac module of the mobility framework and with wich we had to work looking for an optimization.
On the opposite we have seen that the delayed schemes conduct to a better energy consumption and therefore to an extension of the system lifetime.
So there is a trade off between them, and it would be seasonable choose the one that is closer to the requirement.

An interesting work would be to evaluate the performance of a cooperative spectrum sensing scheme that select an OR rule or a majority rule according to the channel quality of the nodes.

Part II

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