THRESHOLD OPTIMIZATION OF ENERGY DETECTOR USING FUZZY LOGIC FOR COGNITIVE RADIO

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Abstract

A spectrum sensing cognitive radio in an interference avoiding behavior has been modeled and simulated using Matlab communication and DSP tool boxes. It is implemented using Mamdani Fuzzy Inference system and Sugeno Fuzzy Inference System. These two fuzzy Inference systems were used to optimize the threshold value for the energy detector scheme used in the spectrum sensing cognitive radio. The results showed that the Sugeno Fuzzy Inference System gave a better performance than that of Mamdani Fuzzy Inference System, while Sugeno Fuzzy Inference System gave an optimized threshold of 9.5dB representing a percentage increase of 32.143% that of Mamdani Fuzzy Inference System gave an optimized threshold value of 11dB representing a percentage increase of 21.428%. It is therefore recommended that Sugeno Fuzzy Inference System be used to optimize the threshold for energy detector in a cognitive radio system.

Keywords: Cognitive radio, energy detector, fuzzy Logic

Introduction

The increasing use of wireless devices and application has led to a continuous increasing demand for RF spectrum but the static allocation of spectrum bands to specific applications for specified period of time has rendered the RF spectrum as being “scare”, therefore the need to develop ways of effectively managing the RF spectrum. Cognitive radio provides solution to the problem of “scarcity” or “underutilization” of frequency spectrum. The use of cognitive radio became necessary after it was discovered that a higher percentage of the licensed spectrum is underutilized (Qaraqe et al, 2010; Joonas et al, 2012). Cognitive radio is therefore introduced to efficiently maximize spectrum usage. This implies that cognitive radio can effectively utilize the unused portion of the spectrum that has been licensed out but not been used by the licensed user in time, frequency and space. The Cognitive Radio is expected to do so without causing interference to the licensed user. In other to achieve this, the Cognitive user must be able to sense the frequency spectrum to determine the absence or presence of the licensed user, a process referred to as spectrum sensing.

Spectrum sensing is therefore the first responsibility to be carried out by the cognitive user. Several spectrum sensing methods exist among which are: matched filter, energy detector and cyclostationary feature detector (Akyildiz, Lee and Chowdhury, 2009). The accuracy of the result of the sensed frequency spectrum is subject to the set threshold in the case of an energy detector sensing method. The most important process that defines the performance of energy detection is the setting of detection threshold. The strength of the primary signal perceived by the cognitive user may be reduced by changing environmental conditions therefore, considering a high threshold value, may cause the secondary user not to detect the presence of the licensed user, and possibly interfere with primary transmissions a situation referred to as missed detection. On the other hand, if
the threshold value is too low, then the detector will become susceptible, and thus indicate the presence of licensed users, even if they are not present a situation referred to as false alarm detection. This may lead to poor spectrum utilization by secondary users, even when opportunities are present. Therefore, in order to mitigate this, we propose the use of an optimum threshold. The optimum threshold is determined by fuzzy logic Inference System (FIS), an algorithm written to determine optimum threshold value within a cognitive radio model.

Two methods of fuzzy logic Inference Systems have been considered in this work, one is the Mandani type fuzzy logic and the other is the Sugeno type fuzzy logic. The two have been used to optimize the threshold of an energy detector sensing cognitive radio. The results of the two are then compared to determine a more suitable algorithm for the optimization of an energy detector sensing cognitive radio.

**Literature review**

**Related works**
Several works have been done in energy detector as it relates to Cognitive Radio, Joyraj C. (2012) in his work on ANFIS based opportunistic power control for Cognitive Radio in Spectrum Sharing researched into the simultaneous transmission of the primary user and the cognitive user by controlling the transmission power of the secondary user. They stated that improving the performance of the secondary user and minimizing the interference to the primary link are two conflicting goals in a spectrum sharing network. Waleed et al (2012) worked on improved local spectrum sensing for cognitive radio networks. The authors proposed a two-stage local spectrum sensing scheme using conventional sensing technique in the first stage and fuzzy logic in the second stage. The aim was to achieve accuracy and improve reliability while eliminating the cooperative overhead introduced to a cognitive radio network by using cooperative spectrum sensing. Sharma and Singh (2012) proposed a novel approach for Spectrum Access using fuzzy logic in cognitive radio; the authors used fuzzy logic to manage the spectrum access by cognitive radio. Four descriptors in form of antecedents in the fuzzy logic scheme were used. These are the spectrum utilization efficiency of the secondary user, mobility, distance of the primary user and signal strengths of the secondary user. Vijayakumar and Sai, (2014), in their research on cognitive radio network formed by configuring Zigbee as primary user and secondary user on a microcontroller ATMEL ATMEGA328P based Arduino board. Using the parameters of signal strength, transmit power level and routing algorithm, fuzzy logic was used to make the decision for the appropriate transmit power level that will reduce interference.

**Cognitive radio spectrum sensing**
Spectrum sensing involves the detection, by a given receiver, of the presence of a transmitted signal of interest (Cabric, Thachenko and Broadersen, 2006; Yucek and Arslan, 2009). Spectrum holes, that is, available channels must be sensed for opportunistic spectrum access. Since spectrum holes are due to idle state where there are no signal transmissions of primary users, to identify them, the secondary users must detect the absence of primary signals in that given frequency band. This task can be viewed as a binary hypothesis testing problem in which Hypothesis 0 ($H_0$) and Hypothesis 1 ($H_1$) are the primary signal absent and primary user present respectively. Spectrum holes are therefore identified when $H_0$ is true.

**Energy detection**
Energy detection is a detection technique that measures the signal power of the received signal and compares it with a predetermined threshold to decide whether the channel is vacant or not. If the threshold is exceeded, it is decided that signal(s) is (are) present otherwise it is absent (Rao et al, 2010; Verma, Taluja and Dua, 2012).

Figure 1: Block diagram of energy detector

![Block diagram of energy detector](source)

The performance of energy detector is characterized by using the metrics of false alarm probability, missed detection and detection probability under binary hypothesis based on the test statistics (Attapattu, Tellambura and Jiang, 2014).

**False alarm probability (**$P_f$**):** this is the probability of deciding that the signal is present while in actual fact it is not. In the context of cognitive radio networks, a false alarm results in undetected spectrum holes therefore a large $P_f$ contributes to poor spectrum usage by secondary users. In terms of binary hypothesis, false alarm probability can be expressed as (Biglieri et al, 2013):

$$P_f = P_r \left[ \frac{H_1}{H_0} \right]$$

Where:
- $P_f$ is the probability of false alarm
- $P_r \left[ \frac{H_1}{H_0} \right]$ is the probability of declaring $H_1$ under $H_0$ hypothesis

**Missed detection probability (**$P_{md}$**):** this is the probability of deciding that the signal is absent while the signal is actually present. In the context of cognitive radio networks, a missed detection is identifying a spectrum hole where there is none. Therefore a large $P_m$ contributes to unexpected interference to
primary users. In terms of binary hypothesis, missed detection probability can be expressed as (Rao et al, 2010):

$$P_{md} = P_r[H_0/H_1]$$

Where:

- $P_{md}$ is the probability of missed detection
- $P_r[H_0/H_1]$ is the probability of declaring $H_0$ under $H_1$ hypothesis

**Detection probability ($P_d$):** this is the probability of deciding that the signal is present when the signal is actually present. In the context of cognitive radio networks, a detection is identifying a spectrum hole where there is one therefore a large $P_d$ is desired to efficiently utilize the RF spectrum. In terms of binary hypothesis, detection probability can be expressed as (Rathi, Dua and Singh, 2011)

$$P_d = P_r[H_1/H_1]$$

Where:

- $P_d$ is the probability of detection
- $P_r[H_1/H_1]$ is the probability of declaring $H_1$ under $H_1$ hypothesis

For an energy detector $P_f$ and $P_d$ can be expressed as (Attapattu, Tellambura and Jiang, 2014):

$$P_f = \frac{\Gamma\left(\frac{N}{2}, \frac{\lambda}{2\sigma_w^2}\right)}{\Gamma(N)}$$

and

$$P_d = Q_N\left(\frac{\sqrt{2N\gamma}}{\sigma_w} \sqrt{\frac{\lambda}{\sigma_w^2}}\right)$$

Where:

- $\Gamma(n) = \int_0^\infty t^{n-1}e^{-t}dt$ is the Gamma function
- $\Gamma(n, x) = \int_x^\infty t^{n-1}e^{-t}dt$ is the upper incomplete gamma function
- $\lambda$ is the threshold
- $\sigma_w$ is the noise variance
- $N$ is the number of samples
- $\gamma$ is SNR
- $Q_N(a, b) = \int_b^\infty x(x^2 + b^2)^{(-N/2)}I_{N-1}(ax)dx$ is the generalized Marcum-Q function.

The test statistics of an energy detector which is also the output of the digital integrator is given by (Attapattu, Tellambura and Jiang, 2014):

$$\Lambda = \sum_{n=1}^{N} |y(n)|^2$$

Given that:

- $\Lambda$ is the test statistics
- $y(n)$ is the received signal
- $N$ is the number of samples

Therefore, in terms of test statistics;

The detection probability can be expressed as (Rathi, Dua and Singh, 2011):

$$P_d = P_r[\Lambda > \lambda | H_1]$$

The false alarm probability can be expressed as: (Rao et al, 2010):

$$P_f = P_r[\Lambda > \lambda | H_0]$$

And missed detection is given by:

$$P_{md} = 1 - P_d$$

Where $\lambda$ is the threshold.
A high $P_{md}$ would result in missing the presence of the primary user on the contrast, a high $P_f$ means that the secondary user observes the primary user while it does not exist which turns out to be low spectrum utilization.

**Fuzzy inference system (FIS)**

Fuzzy inference system is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides the basis from which decisions can be made or patterns discerned. This process involves membership functions, logical operations and if-then rules. (Frank, 2013; Hazlina and Jonathan, 2010)

**Types of inference system**

There are two types of Fuzzy Inference methods that are commonly used, these are (Kaniezhil, Daniel, and Prakash, 2013),

1. The Mamdani method
2. The Sugeno method.

Mamdani Method has the advantages that, It is intuitive, It has widespread acceptance and It is well suited to human input while Sugeno Method has the advantages that, It is computationally efficient, It works well with linear techniques (e.g., PID control), It works well with optimization and adaptive techniques, It has guaranteed continuity of the output surface and It is well suited to mathematical analysis (Arshdeep and Amrit, 2012).

**Modeling, simulation and analysis**

In other to implement the Mamdani type fuzzy logic and Sugeno type fuzzy logic algorithms, a cognitive radio was modeled using MATLAB and simulated. This is depicted in figure 2.

**Operation of the CR model**

Figure 2 shows the diagram of the cognitive radio model. This model consists of the primary user, secondary user, energy detector, and fuzzy logic controller. The primary user generates the signals that are sensed by the secondary user. The secondary user runs the energy detector algorithm which is the main feature in sensing on the cognitive radio system. The sensed energy is then processed for the presence or absence of primary user on the transmission spectrum. The certainty of the presence or absence of the primary signal is the main task to be determined as this could lead to either false alarm or missed detections by secondary user who wish to transmit opportunistically on the primary user’s spectrum band. The MATLAB program code for the cognitive radio is displayed in Appendix A. The fuzzy logic controller implements the fuzzy logic algorithms for optimization of the threshold. The algorithm to test the incoming energy requires setting of a benchmark or threshold for detection which gives a near perfect judgment of spectrum state before subsequent decision is taken by the SU to transmit or not. The setting of this threshold in the midst of sensing uncertainty is achieved through analysis of the sensed energy which in this case is done by the fuzzy logic algorithm. The algorithms seek to harness the inherent strengths of FL to achieve an optimal threshold value for correct detection of the PU behavior. For optimization purposes, the sensed energy is analyzed and inferences drawn on the suitable detection threshold in the light of the prevailing SNR on the transmission channel. The SNR is a significant working parameter especially in the energy detector scheme as it determines the suitability of this detection scheme for the use in CR sensing and detection of primary user activity. Carrying out several simulations of the program, it is
possible to see the range of results for the energy values obtained for the set of working parameters chosen. This serves as a guide for the setting of the allowable threshold range in the fuzzy logic graphical user interface (GUI). It must be recalled that fuzzy inference system uses prior knowledge of the system to set system parameters. Therefore, an allowable SNR of between 14dB and 17dB is used as a guide for this work. From a logical point of view, the values of sensed energy are functions of working parameters such as transmission carrier frequency, message frequency, prevailing environmental interferences etc. therefore, for the purpose of simulation, it is assumed that there is no control over the received energy at the energy detector except for the Bernoulli generator which turns ON and OFF the transmissions from the PU.

![Cognitive radio model](image)

**Fuzzy logic analysis**

The inputs used in this work are the energy derived from the energy detector and the change in energy while the output is the optimized value of the threshold as shown in table 1.

Table 1: Description of fuzzy inputs and outputs

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
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<tbody>
<tr>
<td>Energy (dB)</td>
<td>Optimized threshold(dB)</td>
</tr>
<tr>
<td>Change in energy(dB)</td>
<td></td>
</tr>
</tbody>
</table>

Figure (3 and 4) shows a part of the result of the pseudocode for the FIS. This work has made use of two inputs and seven fuzzy membership functions each which amounts to 49 rules in total.
Figure 3: Screen shot of mamdani type FIS

Figure 4: Screen shot of sugeno type FIS

**Optimization of the threshold**

The aim of the work is to determine an optimal threshold value from carrying out fuzzy analysis on the sensed energy signals. From equation 5, it can be seen that probability of false alarm and
probability of missed detection is a function of the threshold therefore; this work seeks to reduce the resultant probability of false alarm and probability of missed detection of energy detector by optimizing its threshold using fuzzy logic algorithms. The sensed energy being a function of the parameter settings made for the CR, is especially sensitive to the SNR value of the operating channel or environment. With the following parameters set, the results obtained for an initial starting value of threshold of 14dB are displayed in table 1. The results gotten from the two types of fuzzy logic algorithms considered are then compared. Figure 4, performs the optimization of the threshold values gotten from the cognitive radio model of figure 2. This model is embedded within the larger model of the CR of figure 5.

![Diagram for Implementation of Fuzzy Logic Algorithm](image)

Figure 5: Diagram for implementation of fuzzy logic algorithm

**Discussion of results**
The results of the two FIS considered are displayed in table 2. From this result, it is seen that the Mamdani Inference method gave an optimized threshold value of 11dB with a 21.428% optimization while Sugeno Inference method produced an optimized threshold value of 9.5dB with a 32.143% optimization for a seed threshold value of 14dB. It is therefore evident from the result shown in table 2 that Sugeno Inference method is better for optimizing the threshold for an energy detector spectrum sensing cognitive radio.

<table>
<thead>
<tr>
<th></th>
<th>Seed threshold</th>
<th>Optimal threshold</th>
<th>% optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mamdani</td>
<td>14dB</td>
<td>11dB</td>
<td>21.428</td>
</tr>
<tr>
<td>Sugeno</td>
<td>14dB</td>
<td>9.5dB</td>
<td>32.143</td>
</tr>
</tbody>
</table>

Performing similar experiment using the Sugeno type algorithm yields a slightly different result for the optimized threshold of about 9.5dB. Even though the results are close, the computational efficiency of the Sugeno system makes for
a better working value for the set threshold.

**Fuzzy rule viewer**
The generated fuzzy surface describes the relationship between the inputs and the outputs in fuzzy logic analysis. It shows a 3D relationship between the inputs and output. This is displayed by the fuzzy rule viewer. Figure 6 shows the result of the fuzzy rule viewer for Mandani type and figure 7 shows the result of the fuzzy rule viewer for the Sugeno type. The slope of this surface gives an indication of the rules used and the strength of result obtained in terms of optimality.

![Surface Viewer: fuzzblockMam](image)

Figure 6: Surface rule viewer for the Mandani type
**Conclusion**

From the results obtained from the simulation and displayed in tables 2 as well as figures 6 and 7, it is evident that the Sugeno type fuzzy logic outperforms the Mamdani type fuzzy logic. It is therefore recommended that the Sugeno type fuzzy logic be used for the optimization of the threshold in an energy detector sensing technique for spectrum sensing cognitive radio.

In this work, we have been able to model and simulate a spectrum sensing cognitive radio in an interference avoiding behavior and implemented it using Mamdani Fuzzy Inference system and Sugeno Fuzzy Inference System. These two fuzzy Inference systems were used to optimize the threshold value for the energy detector scheme used in the spectrum sensing cognitive radio.

The results showed that the Sugeno Fuzzy Inference System gave a better performance than that of Mamdani Fuzzy Inference System, while Sugeno Fuzzy Inference System gave an optimized threshold of 9.5dB representing an a percentage increase of 32.143% that of Mamdani Fuzzy Inference System gave an optimized threshold value of 11dB representing a percentage increase of 21.428%.

Further work can be carried out by modeling and simulating a spectrum sensing cognitive radio using a cyclostationary feature detector as the detecting technique. The results of this scheme can be analyzed and compared with that of the energy detector sensing technique.

**References**


Radio”, Springer, New York pp 11-26


