Performance Evaluation of Cluster Based Cooperative Cognitive Radio Network

M. Moradkhani, Z. Zalani

***Abstract*— Cognitive radio is regarded as one of the transformational technologies that play a fundamental role in establishment and development of next generation wireless networks. Clustering based cognitive radio networks can reduce the energy consumption and increase the spectrum sensing accuracy. In this paper, we investigate the performance of a cognitive radio network with a clustering architecture for cooperative spectrum sensing. The network efficiency is evaluated in terms of throughput and energy consumption, under fading channel conditions. Simulation results show significant improvement of energy efficiency compared to the conventional non-clustering method by ensuring allowable interference with primary users.**

***Index Terms*—Cluster, Cognitive Radio, Energy Efficiency, Spectrum Sensing**

I. Introduction

THE scarcity of radio spectrum will be one of the major challenges of the communications industry in the coming decades. On the one hand, new high-speed technologies are developing day by day and on the other hand, the current static spectrum allocation policies are very inefficient [1]. To make effective use of spectrum, the idea of cognitive radio (CR) has been suggested; a radio that identifies the frequency environment and adjusts its operational parameters, according to changes in the environmental conditions so that the best QOS is provided [2]. The CR as an unlicensed or secondary user, regularly monitors the allocated spectrum to the licensed or primary user. If an empty channel is detected, It is used by the CR for data exchange, otherwise another channel will be considered. This process is called spectrum sensing. The sensing result of a single secondary user may be unreliable due to the fading and shadowing effects. Cooperative spectrum sensing has been proposed as a solution to this problem in which, the sensing operation is carried out by the cooperation of all or some of the secondary users [3], [4]. Increasing the number of participating radios in sensing process causes more energy to be consumed, while it does not necessarily lead to better detection performance. In fact, cooperation of radios with poor channel conditions, deteriorate the overall network efficiency. In cooperative spectrum sensing, the local result of each radio is reported to a base station called fusion center (FC), through a common control channel. The local binary decisions '0' and '1' represent inactivity and activity of the primary user, respectively.

The final decision regarding the presence or absence of the primary user is taken in the FC, based on a predefined fusion rule. If the final decision indicates the primary user activity, the secondary users remain idle to avoid interference with the primary users. Otherwise, they start data transmission.

Clustering in wireless sensor networks can reduces energy consumption and communication overhead. Furthermore, higher scalability and bandwidth efficiency can be obtained [5], [6]. In this way, the nodes are divided into some clusters and within each cluster, a node is determined as a cluster head. For a cognitive radio network, the local sensing results or local decisions of the secondary users, will be sent to the relevant cluster head. By combination of these local decisions, each cluster head takes the cluster decision and sends it to the FC.

In the literature, some works consider clustering method for cognitive radio networks from different points of view, such as spectrum sensing accuracy [7-9], dynamic allocation of control channel [10] and primary user channel [11], reporting channel bandwidth efficiency [12], spectrum hand off [13-14] and routing protocols[15-17]. In this article, we evaluate the performance of a cognitive radio network based on clustering mechanism in terms of network throughput and energy consumption as well as energy efficiency, which is defined as the ratio of throughput to energy.

Clustering method is expected to reduce the energy consumption, due to preventing direct transmission of local decisions to the FC. In addition to energy consumption, the network throughput is also an important parameter. Its importance in cognitive radio networks is much greater than conventional wireless networks. Because, the acquisition of a frequency channel by a secondary user is temporary and it must vacate the channel as soon as a primary user appears. So it should take full advantage of this opportunity and transfer the maximum amount of data before detection of a primary user. We consider practical situation in which cognitive radios experience different SNR values due to fading effects and also adapt the erroneous reporting channels.

The reminder of the paper is organized as follows: In section 2, the system model is presented. Section 3 deals with the network throughput and energy consumption. Simulation

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results are given in section 4 and finally section 5 concludes the paper.

II. SYSTEM MODEL

Each cognitive radio is equipped with an energy detector. Energy detection is a common method for spectrum sensing because it is simple and requires no previous knowledge of primary signal. Cognitive radio network consists of N secondary users and K clusters. Each secondary user belongs only to one cluster. In each cluster, a radio that has the most reporting channel gain is selected as the cluster head. The reporting channel is a channel between the cognitive radio and the FC through which the local sensing results are sent to the FC. The radios of a cluster compare their received energy with a detection threshold and send the results as binary local decisions to the cluster head. In the cluster head, after combining the local decisions according to a predefined fusion rule, a cluster decision is taken and sent to the FC. All the cluster decisions are then used for taking the final decision.

We adapt the common OR fusion rule in cluster heads and the FC. The outcome of OR rule is '0' only if all of the local decisions are '0'. The probabilities of false alarm and missed detection in a cluster head can be expressed as follows, respectively:

$$Q_{f,i} = 1-(1-P_f)^{N_i} \tag{1}$$

$$Q_{m,i} = P_{m,i}^{N_i} \tag{2}$$

Where i is the cluster number and N_i is the number of cognitive radios in cluster i. P_f and P_m represent the local probabilities of false alarm and missed detection respectively, which are obtained as follows [3]:

$$P_f = \frac{\Gamma(U,\frac{\lambda}{2})}{\Gamma(U)} \tag{3}$$

$$P_{m,i} = 1-e^{-\frac{\lambda}{2}}\sum_{n=0}^{u-2}\frac{1}{n!}(\frac{\lambda}{2})^n + (\frac{1+\bar{\gamma}_i}{\bar{\gamma}_i})^{u-1} \times\left[e^{-\frac{\lambda}{2(1+\bar{\gamma}_i)}} - e^{-\frac{\lambda}{2}}\sum_{n=0}^{u-2}\frac{1}{n!}(\frac{\lambda\bar{\gamma}_i}{2(1+\bar{\gamma}_i)})^n\right] \tag{4}$$

Where U is the time-bandwidth product, λ is the detection threshold and $\bar{\gamma}_i$ represents the average SNR of secondary user i with Rayleigh distribution. $\Gamma(.,.)$ and $\Gamma(.)$ are incomplete gamma function and gamma function, respectively.

After completing the sensing phase in cluster level, each cluster head reports its decision to the FC through a reporting channel. Given that the reporting channels experience Rayleigh fading, the average channel error probability for a BPSK signal is as follows [8]:

$$Q_{e,i} = \sum_{m=1}^{N_i-1}\binom{N_i-1}{m}(-1)^{N_i-m-1}\times(1-\sqrt{\frac{\bar{\rho}_i}{N_i-m+\bar{\rho}_i}}) \tag{5}$$

Where $\bar{\rho}_i$ is the average reporting channel SNR of cluster i. A cluster decision, after passing through the reporting channel, would be true if one of the following occurs:

1) The cluster decision is correct and the reporting channel is error-free.

2) The cluster decision is incorrect and the reporting channel contains error.

Therefore, the final probabilities of false alarm and missed detection become as follows:

$$Q_f = 1-\prod_{i=1}^{K}\left[(1-Q_{f,i})(1-Q_{e,i})+Q_{f,i}Q_{e,i}\right] \tag{6}$$

$$Q_m = \prod_{i=1}^{K}\left[Q_{m,i}(1-Q_{e,i})+(1-Q_{f,i})Q_{e,i}\right] \tag{7}$$

III. THROUGHPUT

Cooperative spectrum sensing includes three phases; sensing, reporting and transmission. In sensing phase, all cognitive radios perform local sensing based on energy detection. Reporting phase consists of two steps: First, reporting of local decisions taken by cognitive radios of each cluster to the relevant cluster head and second, reporting of cluster decisions by their cluster heads to the FC. If the final decision indicates absence of the primary user, then the operation of cognitive radio network changes to transmission phase.

In other word, if the cognitive radio network confirms absence of the primary user correctly or falsely, it enters to transmission phase. The probability of the former case occurrence is equal to $P(H_0)(1-Q_f)$ and for the latter case it is equal to $P(H_1)Q_m$, where H_0 and H_1 denote the inactivity and activity of the primary user, respectively.

Each slot time contains three parts: sensing time, reporting time and transmission time. In each cluster including N_i radios, N_i-1 radios send their local decisions to the cluster head. Assuming K as the number of clusters, the total number of cognitive radios sending their decisions to their own cluster heads are $\sum_{i=1}^{K}(N_i-1) = N-K$. Moreover, K cluster heads report their cluster decisions to the FC.

Let denote t_{r_1} as the reporting time from a radio within a cluster to its own cluster head and t_{r_2} as the reporting time of a cluster head to the FC. Thus, the transmission time becomes $T-(N-K)t_{r_1}-Kt_{r_2}$, where T is the slot time. According to the above explanations, the network throughput can be formulized as follows:

$$R=(\frac{T-\tau-Mt_{r_1}-Kt_{r_2}}{T})[P(H_0) .(1-Q_f)r_0+P(H_1)Q_m r_1] \quad (8)$$

Where r_0 and r_1 denote the network throughput in the absence and presence of the primary user, respectively. When both primary and secondary users are active, the throughput decreases due to interference, so $r \prec r_0$. Furthermore, the use of cognitive radio technology is affordable in situations that the primary user is more likely to be inactive, i.e. $P(H_1)\prec P(H_0)$. So the second term of equation (8) can be disregarded:

$$R=(\frac{T-\tau-Mt_{r_1}-Kt_{r_2}}{T})P(H_0)(1-Q_f)r_0 \quad (9)$$

IV. ENERGY CONSUMPTION

The energy consumption of sensing phase, due to participation of all radios, is equal to $N\tau P_s$ where P_s is the power of a cognitive radio during sensing. The reporting energy consumption is $(N-K)t_{r_1}P_{r_1}$, within the clusters and $Kt_{r_2}P_{r_2}$ between cluster heads and the FC, where P_{r_1} and P_{r_2} are the cognitive radio powers in these reporting phases, respectively. Thus, we can represent the energy consumption of both reporting and sensing phases as follows:

$$E_1=N\tau P_s+Mt_{r_1}P_{r_1}+Kt_{r_2}P_{r_2} \quad (10)$$

And, denoting P_t as the transmission power, the transmission phase energy consumption becomes:

$$E_2=[T-\tau-(N-K)t_{r_1}-Kt_{r_2}]P_t P(H_0)(1-Q_f) \quad (11)$$

Since, there is a tradeoff between the network throughput and energy consumption, it is better to bring them together in a single parameter. We use the energy efficiency, which is a common metric and defined as the ratio of throughput to energy consumption.

V. SIMULATION RESULTS

We consider a cognitive radio network with 8 secondary users. The network is divided into two clusters, one includes five and the other three secondary users. The received SNRs of the primary user signal by the first and second clusters are -10dB and -7dB, respectively. The reporting channels SNRs of cognitive radios within cluster 1 are [3,5, 6,7,10] dB, and for cluster 2 [4,5,8]dB. We also consider different reporting channel SNR values to represent reporting channels with different error probabilities. In each cluster, a radio with the highest reporting channel SNR, is selected as a cluster head.

Sampling frequency is 1 MHZ, slot time is 10 ms and sensing time is 1 ms. Fig. 1 shows the probability of total detection error versus detection threshold. This error occurs when the primary user is active but the cognitive radio network recognizes it mistakenly as inactive (missed detection), or the primary user is inactive but the cognitive radio network declares its activity (false alarm). Therefore, it can be represented as $q_e=P(H_0)Q_f+P(H_1)Q_m$.

It is observed that the total detection error of the proposed method has decreases compared with the conventional (non-clustering) method. Because in the clustering method, the cluster heads that have the highest SNR among their neighboring radios, exchange data with the FC. So, the reported data are less susceptible to error, resulting in higher sensing performance.

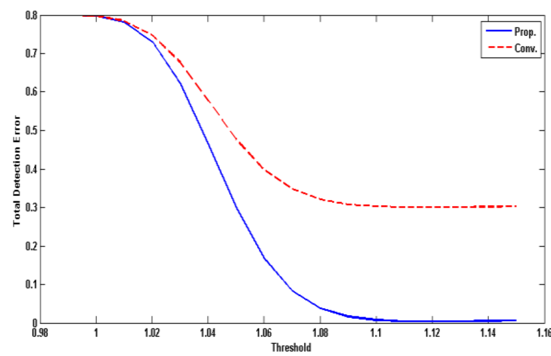

Fig. 1. Total detection error probability versus detection threshold

Fig. 2 shows the normalized throughput in terms of sensing time. The general missed detection probability is set to 0.001 and the reporting times from a cognitive radio to its own cluster head and from a cluster head to the FC are set to 0.01 ms and 0.1 ms, respectively. The proposed method reaches higher throughput for different sensing times, so that the maximum throughput improvement is about 70%.

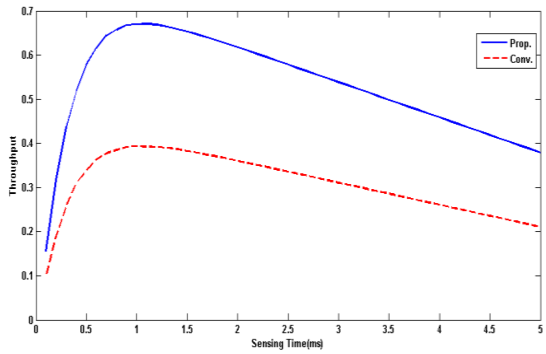

Fig. 2. Normalized throughput versus sensing time

According to Fig. 3, the total energy consumption of sensing and reporting phases of clustering method decreases. In fact, instead of sending all local sensing results directly to the FC, they are sent to their cluster heads and then just cluster decisions will be reported to the FC. Thus, more energy will be saved.

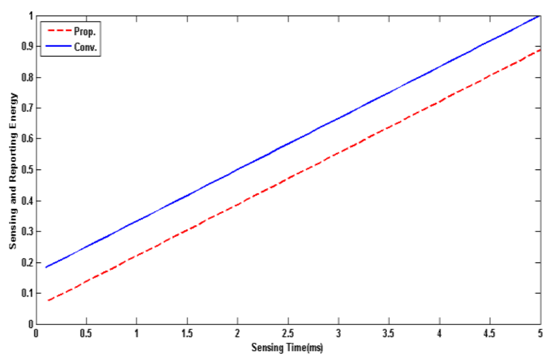

Fig. 3. Energy consumption versus sensing time

Fig. 4 depicts the energy efficiency as a function of sensing time. The energy efficiency of the clustering method at different sensing times is more than the conventional method. The percent increase in energy efficiency is highly dependent on sensing time, so that at the optimal sensing time i.e. 0.4 ms, in which maximum energy efficiency is achieved, the percent increase in energy efficiency is also maximum. At longer sensing times the percent improvement of energy efficiency is reduced, due to throughput reduction and rising energy of sensing phase.

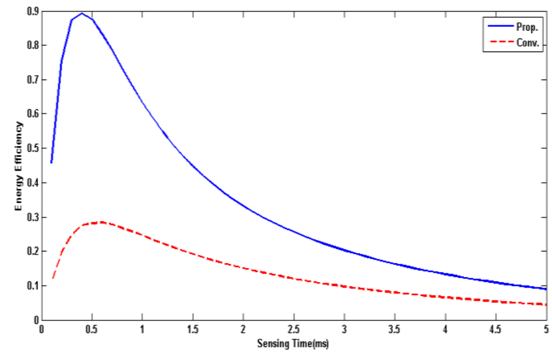

Figure 4. Energy efficiency versus sensing time

Fig. 5 demonstrates the maximum achievable throughput in different SNRs. Also the effect of SNR on maximum achievable energy efficiency is shown in Fig. 6. Obviously, the clustering method performance is much better than the conventional method, specially for higher SNR values. Although the performance of both methods degrade at low SNRs because of more detection error, but the superiority of the cluster based method still remains.

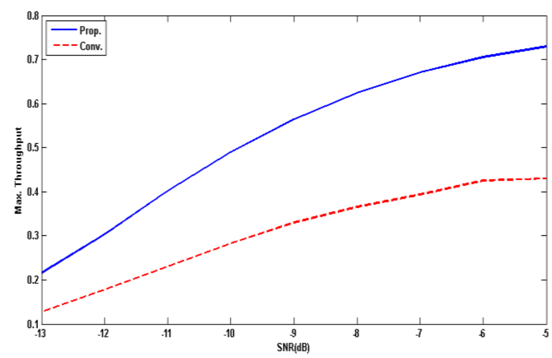

Figure 5. Maximum network throughput versus SNR

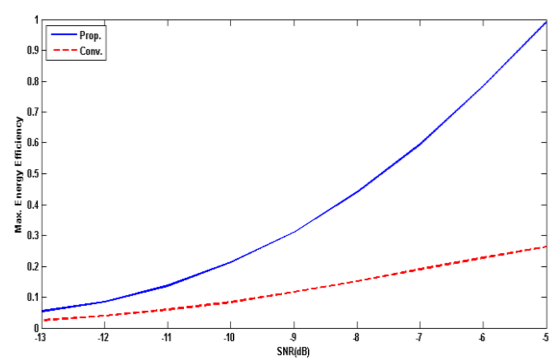

Figure 6. Maximum energy efficiency versus SNR

VI. CONCLUSION

In this paper, we examined the performance of clustering method for cooperative spectrum sensing in cognitive radio networks. It was shown that the clustering method lowers the total detection error, as well as energy consumption of reporting and sensing phases. Furthermore, by optimal sensing time setting, the maximum network throughput and energy efficiency dramatically improve.

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