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인지무선네트워크를 위한 고유값 및 중첩기반의 협력 스펙트럼 센싱 기법

A Cooperative Spectrum Sensing Method based on Eigenvalue and Superposition for Cognitive Radio Networks

미아시폰*, 구인수**

Md. Sipon Miah, Insoo Koo

요 약 단일 노드 스펙트럼 센싱과 비교했을 때, 협력스펙트럼 센싱은 스펙트럼 센싱의 신뢰도를 크게 향상 시킬 수 있다. 또한 고유값(Eigenvalue)기반의 스펙트럼 센싱 기법은 에너지 검출 기반의 센싱 기법에 비해 센싱 성능을 제공할 수 있기 때문에 최근 많은 관심을 끌고 있다. 고유값(Eigenvalue)기반의 스펙트럼 센싱 기법의 성능은 smoothing factor (SF)가 증가함에 따라 더 좋은 센싱 결과를 얻을 수 있으나, SF값이 증가함에 따라 더 긴 센싱 시간이 요구된다. 더나가 협력 스펙트럼의 경우, 노드수가 증가함에 따라 더 많은 전송시간이 요구됨으로, 고유값(Eigenvalue)기반의 협력 스펙트럼 센싱의 경우 SF값이 센싱 시간을 결정하는 중요한 요소가 된다. 이에 본 논문에서는 센싱 시간을 증가하지 않고 SF값을 증가시킬 수 있는 고유값 및 중첩기반의 협력 스펙트럼 센싱 기법을 제안한다. 제안된 방식에서는 SF값을 증가시키기 위하여 전송(reporting) 시간을 활용한다. 시뮬레이션을 통해 제안된 방식이 기존 고유값(Eigenvalue)기반의 센싱기법에 비교하여 더 작은 센싱 시간을 유지하면서 국부(local) 센싱값 및 전체(global) 센싱값을 향상 시킬 수 있음을 보였다.

Abstract Cooperative spectrum sensing can improve sensing reliability, compared with single node spectrum sensing. In addition, Eigenvalue-based spectrum sensing has also drawn a great attention due to its performance improvement over the energy detection method in which the more smoothing factor, the better performance is achieved. However, the more smoothing factor in Eignevalue-based spectrum sensing requires the more sensing time. Furthermore, more reporting time in cooperative sensing will be required as the number of nodes increases. Subsequently, we in this paper propose an Eigenvalue and superposition-based spectrum sensing where the reporting time is utilized so as to increase the number of smoothing factors for autocorrelation calculation. Simulation result demonstrates that the proposed scheme has better detection probability in both local as well as global detection while requiring less sensing time as compared with conventional Eigenvalue-based detection scheme.

Key Words : Cognitive radio network, spectrum sensing, eigenvalue, superposition

*준희원, 울산대학교, 전기공학부

**정희원, 울산대학교, 전기공학부 (교신저자)

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**Corresponding Author: iskoo@ulsan.ac.kr

School of Electrical Engineering, University of Ulsan, Korea

I. Introduction

Cognitive Radio (CR) [1][2][15] as a revolutionary intelligent technology can maximize the utilization of the frequency resources by allowing secondary users to access the spectrum bands allocated to Primary Users when they are idle temporally. Energy detection scheme can be used by a single Cognitive Radio User (CRU) for idle spectrum. However, it can not deal with the hidden terminal problem [3][16] which arises due to multi-path fading and shadow effect, which results in severe performance degradation. Recently, cooperative spectrum sensing scheme was proposed to overcome the hidden terminal problem in single node sensing [4][5][6][7]. To implement conventional cooperative spectrum sensing, each CRU makes a local decision and those decisions are reported to a fusion center to make a final decision according to some fusion rules (e.g. OR, AND, Half voting, Majority rule etc.). However, more reporting data are required for each CRU to report its local decision to a fusion center as the number of cooperative user's increases. Subsequently, more reporting time will be required.

As the energy detection relies on knowledge of noise power, inaccurate estimation of the noise power will lead to high probability of false alarm as well as miss detection [8]. Recently, many papers have investigated the application of Eigenvalue-based spectrum sensing which outperforms energy detection methods [9][10]. In Eigenvalue-based spectrum sensing, covariance matrix of the received signal was used for spectrum detection. In [11], T. Ratnarajah et. al. performed asymptotic analysis of exact decision thresholds for maximum Eigenvalue detector (MED) and maximum - minimum Eigenvalue (MME) detector. They also pointed out that MED has better spectrum detection probability.

In this paper, we propose a minimum-maximum Eigenvalue and superposition-based cooperative detection method. The performance of Eigenvalue-based cooperative detection depends on smoothing factors. The larger smoothing factor will result in the better

sensing performance. However, it will cause larger sensing time. Thus, to achieve better performance within given sensing time, in this paper a superposition approach [12] is applied to the Eigenvalue-based cooperative detection method. In the proposed scheme, a CRU will utilize other CRUs' report time for sensing more samples. Thus, a significant detection performance improvement can be achieved without extra spectrum sensing time. With the best of our acknowledge, the application of the superposition approach to Eigenvalue-based spectrum sensing is not considered in other literatures so far.

Remaining of the paper is structured as follows. In Section II, we introduce the minimum-maximum Eigenvalue-based detector. In Section III, we propose the Eigenvalue and superposition-based cooperative spectrum sensing scheme. In Section IV, simulation results are shown, and conclusion of the paper is drawn in Section V.

II. System Model

For secondary user i ($i = 1, 2, \dots, Q$), the spectrum sensing is a binary hypothesis test that can be formulated as follows [13][14]:

$$\begin{cases} H_0 : y_i(t) = \eta_i(t) & t = 1, 2, \dots, N_x \\ H_1 : y_i(t) = x_i(t) + \eta_i(t) & t = 1, 2, \dots, N_x \end{cases} \quad (1)$$

where t and N_x is the sample index and total number of samples respectively, $x_i(t)$ is the transmitted signal samples, through a wireless channel consisting of path loss, multipath fading and time dispersion effects, and $\eta_i(t)$ is independent and identically distributed (i.i.d) with zero mean Additive White Gaussian Noise (AWGN), i.e. $N(0, \sigma_\eta^2)$. The mean and variance of $x_i(t)$ are zero and σ_x^2 , respectively as well.

For the time series $x_i(t)$, the following two probabilities are concerned in spectrum sensing:

- Probability of detection P_d which defines, at hypothesis H_1 , the probability of the sensing algorithm having detected the presence of the primary signal, and
- Probability of false alarm P_f , which defines, at hypothesis H_0 , the probability of the sensing algorithm identifying the presence of the primary signal.

Let us consider F consecutive smoothing factor. We can define the following matrix for H_1 hypothesis:

$$\begin{bmatrix} y_i(t) \\ y_i(t-1) \\ \dots \\ y_i(t-F+1) \end{bmatrix} = \begin{bmatrix} x_i(t) \\ x_i(t-1) \\ \dots \\ x_i(t-F+1) \end{bmatrix} + \begin{bmatrix} \eta_i(t) \\ \eta_i(t-1) \\ \dots \\ \eta_i(t-F+1) \end{bmatrix} \quad (2)$$

and also we can define the following matrix for H_0 hypothesis:

$$\begin{bmatrix} y_i(t) \\ y_i(t-1) \\ \dots \\ y_i(t-F+1) \end{bmatrix} = \begin{bmatrix} \eta_i(t) \\ \eta_i(t-1) \\ \dots \\ \eta_i(t-F+1) \end{bmatrix} \quad (3)$$

The statistical covariance matrices of the signal and noise can be defined as

$$\mathbf{C}_Y = E[\mathbf{Y}_i(t)\mathbf{Y}_i^T(t)] \quad (4)$$

$$\mathbf{C}_X = E[\mathbf{X}_i(t)\mathbf{X}_i^T(t)] \quad (5)$$

where

$$\begin{aligned} \mathbf{Y}_i(t) &= \begin{bmatrix} y_i(t) \\ y_i(t-1) \\ \dots \\ y_i(t-F+1) \end{bmatrix} \\ &= [y_i(t), y_i(t-1), \dots, y_i(t-F+1)]^T \end{aligned} \quad (6)$$

$$\begin{aligned} \mathbf{X}_i(t) &= \begin{bmatrix} x_i(t) \\ x_i(t-1) \\ \dots \\ x_i(t-F+1) \end{bmatrix} \\ &= [x_i(t), x_i(t-1), \dots, x_i(t-F+1)]^T \end{aligned} \quad (7)$$

, the superscript $(.)^T$ stands for transpose, and $E(.)$ stands for expectation operation. We can verify the covariance matrix \mathbf{C}_Y under the two hypotheses that

$$\mathbf{C}_Y = \begin{cases} \mathbf{C}_X + \sigma_\eta^2 \mathbf{I}_F, & H_1 \\ \sigma_\eta^2 \mathbf{I}_F, & H_0 \end{cases} \quad (8)$$

If the signal $x_i(t)$ is not present, then the covariance matrix of transmitted signal, $\mathbf{C}_X = 0$. If the signal $x_i(t)$ is present, then the covariance matrix of transmitted signal, $\mathbf{C}_X \neq 0$.

The Eigenvalue have the following characteristics: Firstly, the covariance matrix \mathbf{C}_Y is a symmetrical matrix. All Eigenvalues are the real numbers, and the sum of all Eigenvalues is related to the number of cognitive users Q and smoothing factor F . Secondly, if the samples of cognitive users are completely uncorrelated, matrix \mathbf{C}_Y is a unitary matrix and all Eigenvalues are equal to 1. This situation corresponds to the assumption H_0 . Finally, if the samples of cognitive users are completely correlated, all the elements of matrix \mathbf{C}_Y are 1s, and the maximum Eigenvalue is equal to the number of cognitive users Q . This situation corresponds to the assumption H_1 .

In practice, the statistical covariance matrix can only be calculated by using a limited number of signal samples. Let's define the sample auto-correlations of the received signal as following:

$$A(k) = \frac{1}{N_x} \sum_{n=1}^{N_x} y_i(n)y_i(n-k), \quad k = 1, \dots, F \quad (9)$$

where N_x is the total number of available samples. The statistical covariance matrix \mathbf{C}_Y can be approximated by the sample covariance matrix, $\dot{\mathbf{C}}_Y$ defined as

$$\dot{\mathbf{C}}_Y(N_x) = \begin{bmatrix} A(1) & A(2) & \cdots & A(F) \\ A(2) & A(1) & \cdots & A(F-1) \\ \cdots & \cdots & \cdots & \cdots \\ A(F) & A(F-1) & \cdots & A(1) \end{bmatrix} \quad (10)$$

III. Proposed Eigenvalue and Superposition-Based Cooperative Spectrum Sensing Scheme

1. Conventional Eigenvalue-Based Spectrum Sensing

To find sample auto-correlations of the received signal expressed by Eq.10, in the Eigenvalue based spectrum sensing, the essential number of computational time for a single user can be calculated as [10]

$$T_{ssc} = F \times N_x \quad (11)$$

From above equation it is obvious that for a fixed number of samples, the sensing time is dependent on the number of smoothing factor.

In conventional system of Eigenvalue based detection, if we increase the smoothing factor, the necessary sensing time will be increased. The total time, denoted by T_t , consists of sensing time T_s and reporting time T_r . When the number of secondary users is Q , the total time in the conventional Eigenvalue-based detection can be calculated as following:

$$T_t = T_s + Q \times T_r \times N_x \sum_{i=1}^4 F_i \quad (12)$$

where $F_1 = 4$, $F_2 = 8$, $F_3 = 16$ and $F_4 = 20$.

2. Proposed Eigenvalue and Superposition Based Spectrum Sensing

We propose the following signal detection procedure according to smoothing factor and covariance matrix:

- Select appropriate smoothing factors F and calculate the sample covariance matrix for the fixed samples.
- Determine the minimum Eigenvalue ζ_{\min} and maximum Eigenvalue ζ_{\max} from the sample covariance matrix and calculate their ratio,

$$R_{\min} = \frac{\zeta_{\min}}{\zeta_{\max}}.$$

- Compare R_{\min} with the threshold value l . If $l < R_{\min}$ then the signal is present; otherwise, it is absent.

3. Cooperative Spectrum Sensing Based on Superposition

In the proposed Eigenvalue-based spectrum sensing, the reporting time shown in Eq. 12 is exploited for computational purpose for different number of smoothing factors to calculate the autocorrelation of the sample. The entire CR users in cooperative network have the same number of samples.

Therefore, since the sensing duration is fixed, except first CR, all the nodes have to adopt a different waiting time for its reporting to the fusion centre. As an example, the 2nd CRU can utilize reporting time of 1st CRU for sensing, and 3rd CRU can utilize reporting time of the 1st CRU and the 2nd CRU for sensing and so on. In the proposed Eigenvalue based detection method, this reporting time is utilized to calculate autocorrelation of the signal. The main diagram of the proposed system is shown in Fig. 1. From the Fig. 1, it is observed that, for the lowest smoothing factor ($SF_1 = 4$), total M cognitive radio user (CRU) senses the signal for a fixed duration. In addition, for $SF_2 = 8$, idle reporting time of previous CRUs utilized by $(M+1)^{th}$ to N^{th} CRU for computational

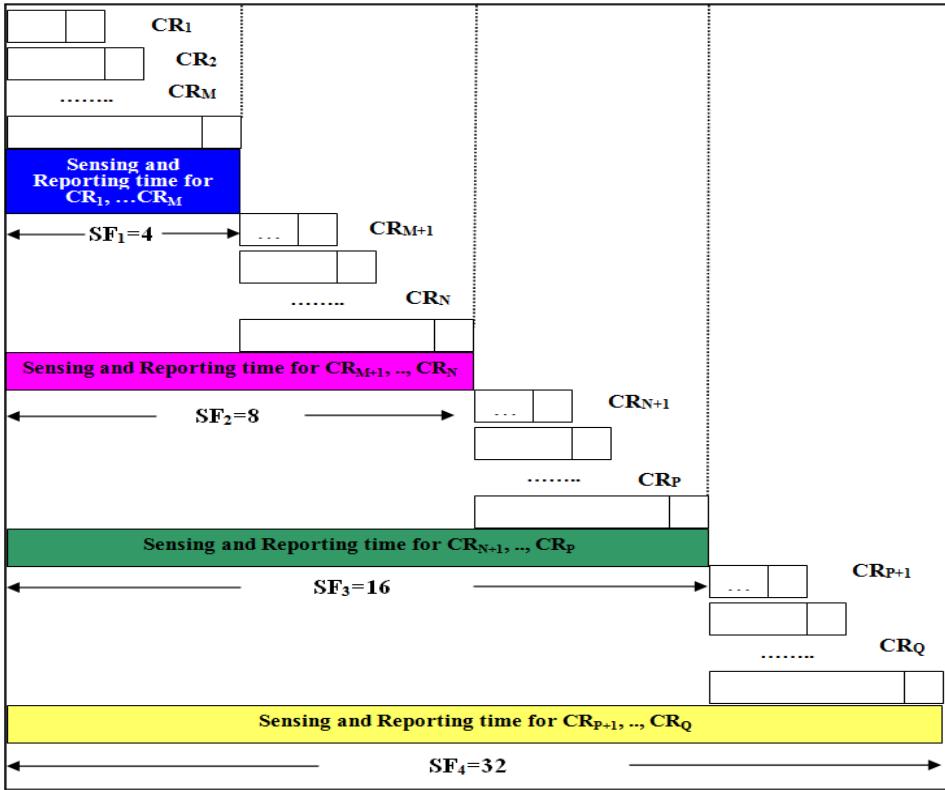


그림 1. Smoothing factor에 따른 제안된 고유값 및 종합기반의 스펙트럼 센싱과정

Fig. 1. Proposed Eigenvalue and superposition-based spectrum sensing with different number of smoothing factor

and reporting purpose can be calculated as:

$$T_{SF_2} = T_s + M \times T_r \quad (13)$$

Likewise, for $SF_3 = 16$ idle reporting time of previous CRUs utilized by $(N+1)^{th}$ to P^{th} CRU for computational and reporting purpose can be written as:

$$T_{SF_3} = T_s + N \times T_r \quad (14)$$

Similarly, for $SF_3 = 20$ idle reporting time of previous CRUs utilized by $(P+1)^{th}$ to Q^{th} CRU for computational and reporting purpose is as:

$$T_{SF_3} = T_s + P \times T_r \quad (15)$$

Therefore, from above three equations it is obvious

that the proposed system utilizes reporting time of previous CRU's for increasing number of smoothing factors. Thus, the required time of the proposed system can be calculated:

$$T_{OPT} = T_s + 4 \times (Q \times T_r \times N_x) \quad (16)$$

IV. Simulation Results

In this section, we evaluate the required normalized time for different number of smoothing factors. From Fig. 2, it is evident that the time complexity is $SF_1 = 4$ increased when the smoothing factors, $SF_2 = 8$, $SF_3 = 16$ and $SF_4 = 32$ are increased

Fig. 3 shows the required normalized times for the

proposed scheme and the conventional scheme. The conventional scheme requires additional time for different number of smoothing factors.

Therefore the conventional system requires the entire time, which is average of all the smoothing factor time. As the proposed system utilizes reporting time for different number of smoothing factor, it does not need to take further time. Rather, it utilizes idle reporting time. Consequently, minimum time is sufficient for its data processing for additional smoothing factors.

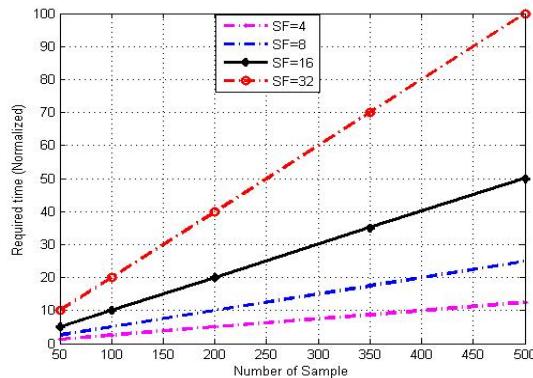


그림 2. Smoothing factor 및 샘플수에 따른 정규화된 센싱시간

Fig. 2. The normalized time for different number of smoothing factors according to the number of samples.

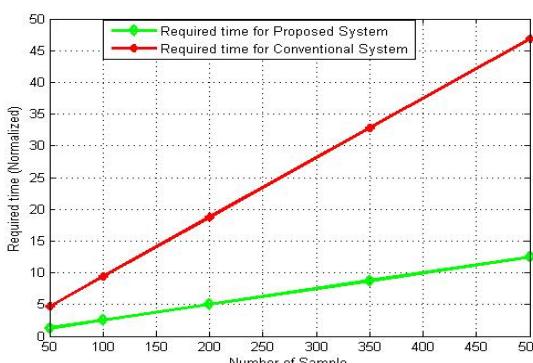


그림 3. 샘플수에 따른 기존 고유값기반 협력 센싱 및 제안된 센싱 기법의 스펙트럼 센싱 시간

Fig. 3. The normalized time of conventional and proposed schemes according to the number of samples

In order to evaluate the proposed scheme, the local sensing performance is shown in the Fig. 4 for different number of smoothing factors. For the simulation, the following parameters are considered: the sampling frequency is 300 KHz, the local sensing time is 1 millisecond (ms), and the number of samples is 100. Moreover, it is assumed that the signal is independent and identically distributed and the channel is under Additive White Gaussian Noise (AWGN). We have tested 10000 trials. Under such condition, the ROC curves illustrated in Fig. 4 shows that conventional energy detection has the lowest sensing probability of detection whereas the Eigenvalue-based detection has the highest probability of detection. Moreover, the more the smoothing factor, the better the probability of detection.

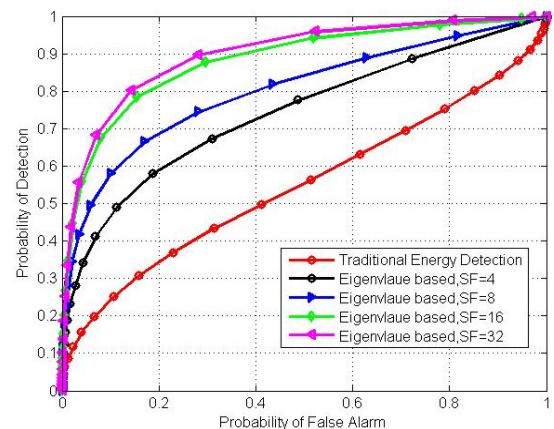


그림 4. Smoothing factor에 따른 기존 에너지 검출 센싱 기법 및 제안된 고유값-기반의 스펙트럼 센싱의 ROC 곡선

Fig. 4. The ROC curves of conventional energy detection and the proposed eigenvalue-based detection for different smoothing factors.

Finally, Fig. 5 shows the global sensing performance for the conventional cooperative Eigenvalue-based detection, and the proposed cooperative Eigenvalue-based detection. For our simulation, it is assumed that there are 8 CRUs where distributed CRUs have different SNR values. The four CRUs execute energy

detection sensing with SNR= -28, -20, -16, and -10. In addition, the remaining CRUs execute Eigenvalue based detection for different number of smoothing factors with random SNR= -28, -20, -16, and -10. We have considered both OR rule and majority rule as a data fusion method. Conventional Eigenvalue-based detection where all CRUs utilize smoothing factor has better performance than traditional energy detection method for both OR and majority rule. However, by utilizing OR rule it is clarified that the proposed method has outperformance over the traditional Eigenvalue based methods and so forth for the majority rule as well. The simulation results prove that the proposed scheme has the ability to significantly improve the sensing performance in CRU networks.

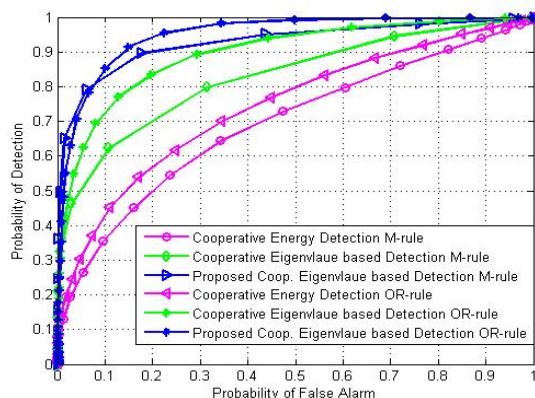


그림 5. 에너지 기간의 협력 스펙트럼 센싱 기법 및 기본 고유 값-기반의 협력 스펙트럼 센싱 기법, 그리고 제안된 협력 스펙트럼 기법의 global 검출 확률 및 오경보 확률

Fig. 5. Global probability of detection and false alarm of cooperative energy detection, conventional cooperative eigenvalue-based detection, and proposed cooperative eigenvalue-based detection

V. Conclusion

In this paper, we have proposed a minimum-maximum Eigenvalue-based cooperative detection method in which different smoothing factors are

utilized based on superposition. Simulation results showed that the proposed scheme provides a better detection probability in both local as well as global detection while maintaining same sensing time.

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저자 소개

미아시폰(준회원)



- 2006년 (학사) Islamic University, Kushtia, Bangladesh
- 2007년 (석사) Islamic University, Kushtia, Bangladesh
- 2012년 ~ 현재 울산대학교 전기공학부 박사 과정

<주관심분야 : 무선센서네트워크, 스펙트럼 센싱>

구 인 수(정회원)



- 1996년 건국대학교 전자공학과 졸업 (학사)
- 1998년 광주과학기술원 정보통신공학과 졸업 (석사)
- 2002년 광주과학기술원 정보통신공학과 졸업 (박사)
- 2005년 ~ 현재 울산대학교 전기공학부 교수

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