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Performance Evaluation of a Cooperative Sensing of OFDM Signal based on Energy and Cyclic Detection

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Abstract Spectrum sensing is one of the most important technique in cognitive radio system. In order to push this system toward the commercial deployment, the effective sensing method is required so that the presence and absence of the primary signals can be identified. Energy detection and cyclic detection are among the most powerful sensing techniques for cognitive radio system. In this paper, the detection performances of a cooperative sensing based on energy detection and cyclic detection are presented.

Key words cognitive radio, signal detection, spectrum sensing, energy detection, cyclic detection

1. Background

Currently, the spectrum resources are not being utilized effectively due to numerous factors. One of these is caused by the drawbacks of the current static spectrum allotment policy. To tackle this problem, the well known cognitive radio (CR) system which would enable flexible, efficient and reliable use of the radio spectrum by adapting the radio's operating characteristics to the environment in real time has been developed [1]– [3]. Today, the CR system is an important consideration in the major spectrum debates in the federal communications commission (FCC) in the United States (US). At the same time, the research community in Japan has also shown strong interest in this system for ubiquitous and spectrum access aspects. However, the ministry of internal affair and communications (MIC) in Japan has not yet released any rules for not only unlicensed but also licensed operation of the CR. Unlike in Japan, the FCC has drafted the first rule for a secondary system based CR to operate in the frequency bands allocated to the television (TV) systems [4] because the usage of the spectrum in these bands is not so high. For example, the IEEE 802.22 working group (WG) in US has been launched to develop a standard of a fixed wireless regional area network (WRAN) which aims at providing wireless broadband access to the rural areas where the need for broadband service has not yet been met due to the physical limitations and economic reality of wire-line solutions, with the performance comparable to those of existing fixed broadband access technologies such as DSL and cable modem [5], [6]. The IEEE 802.22 WG is formulating the WRAN system to operate in the TV bands by opportunistically accessing those bands that are not currently used by TV systems.

The coexistence between the cognitive WRAN and TV system on the same frequency band, time and location poses many challenges. One of which is that the secondary system, i.e. the WRAN system, must be capable of scanning the primary system, i.e. the TV system, so as to recognize and use only vacant channels, and without any impact on the operation of the primary systems. Therefore the effective sensing technique is required so that the presence and absence of the primary signals can be identified. In the presence of knowledge of the primary signals such as modulation scheme, symbol rate, pilot signals etc., replica-correlation detection is one of the most powerful sensing technique or otherwise energy detection and cyclic detection should be considered [7], [8]. Energy detection is the simplest detector that can be constructed in practice. The energy detection is based only on the signal power while the cyclic detection is based on finding the underlying periodicities in the received signal [9]– [14]. The underlying periodicity feature of the received signal often constructs a specific patterns of correlation in the spectral properties of the signal which can be detected even at low signal-to-noise ratio. To overcome the multipath fading or shadowing environment, a cooperative sensing technique where the multiple secondary users collaborate in finding vacant spectrum by sharing the observation informations in order to achieve higher detection performance [15]– [18]. In

this paper, the cooperative sensing techniques based on energy detection and cyclic detection are investigated. The detection performances over additive white Gaussian noise (AWGN) channel of both detectors are evaluated where the primary signal is an orthogonal frequency division multiplexing (OFDM) of integrated services digital broadcasting for terrestrial television broadcasting (ISDB-T) system.

The rest of this paper is organized as follows. In Section 2, a principle of cyclic detector is described. A cooperative sensing techniques are addressed in Section 3. Section 4 presents the simulation results. Finally, Section 5 concludes this paper.

2. Cyclic Detection

2.1 Overview of Cyclostationarity

A zero-mean signal $x(t)$ is called a wide sense second order cyclostationary if its time varying autocorrelation function

$$R_{xx}(t,\tau) = E\{x(t)x^{\star}(t+\tau)\}, \tag{1}$$

is periodic in time t for each lag parameter τ [19]. This autocorrelation function can therefore be represented as the Fourier series

$$R_{xx}(t,\tau) = \sum_{\alpha} R_{xx}^{\alpha}(\tau)e^{j2\pi\alpha t}, \tag{2}$$

where the Fourier coefficient $R_{xx}^{\alpha}(\tau)$ is called the cyclic autocorrelation function (CAF) which is defined as

$$R_{xx}^{\alpha}(\tau) = \lim_{T\to\infty}\frac{1}{T}\sum_{t=0}^{T-1} R_{xx}(t,\tau)e^{-j2\pi\alpha t}, \tag{3}$$

and α is called cyclic frequency. It typically relates to the symbol rate, modulation scheme, carrier frequency etc. A signal $x(t)$ is therefore called cyclostationary if there exists an $\alpha \neq 0$ such that $R_{xx}^{\alpha}(\tau) \neq 0$ for some value of τ.

2.2 Cyclostationarity of OFDM Signal

The complex baseband of OFDM signal can be expressed as follows

$$s(t) = \sum_{n=-\infty}^{+\infty}\sum_{i=0}^{N_c-1} d(n,i)g(t-nT_s) \cdot e^{j2\pi(i-(N_c-1)/2)\Delta f(t-nT_s)}, \tag{4}$$

where $d(n,i)$ is a complex information symbol corresponding to symbol number n and carrier number i, N_c is the total number of carriers, T_s is the total symbol duration, Δf is the carrier spacing and $g(t)$ is the unit rectangular pulse with duration T_s. From [9], it has been shown that the OFDM signal exhibits cyclostationarity at cyclic frequencies

$$\mathcal{P} = \{\alpha : \alpha = \frac{k}{T_s}, k \in \mathcal{Z}\}. \tag{5}$$

Therefore the cyclic autocorrelation function is discrete and composes of peaks at $\alpha = \frac{k}{T_s}$. The OFDM signal must utilize guard interval otherwise it does not exhibit cyclostationarity since its CAF equals zero for $T_s = T_u$.

2.3 Conventional Cyclic Detection

We assume that the received signal $x(t)$ composes of the primary signal $s(t)$ and the additive white Gaussian noise (AWGN) $w(t)$ ($x(t) = s(t) + w(t)$). The detection problem can be stated by the following binary hypothesis test

$$H_0 : x(t) = w(t), \qquad \text{signal is absent} \tag{6}$$

$$H_1 : x(t) = s(t) + w(t), \qquad \text{signal is present} \tag{7}$$

In order to design the cyclic detection it is important to estimate the cyclic autocorrelation function which is consistency with Equation (3). A consistent estimation of CAF can be expressed as [14]

$$\hat{R}_{xx}^{\alpha}(\tau) = \frac{1}{T}\sum_{t=0}^{T-1} x(t)x^{\star}(t+\tau)e^{-j2\pi\alpha t} \tag{8}$$

$$= R_{xx}^{\alpha}(\tau) + \boldsymbol{\epsilon}_{xx}^{\alpha}(\tau), \tag{9}$$

where $\boldsymbol{\epsilon}_{xx}^{\alpha}(\tau)$ is an estimation error which converges toward 0 for $T \to \infty$. $\hat{R}_{xx}^{\alpha}(\tau)$ is therefore rarely zero even if α is not a cyclic frequency because the observation time T is finite. This raises an important issue for designing a decision strategy about whether a given value of α, $\hat{R}_{xx}^{\alpha}(\tau)$ is zero or not. To tackle this problem, a vector of $\hat{R}_{xx}^{\alpha}(\tau)$ is considered rather than a single value [14]. A 1×2 row vector containing the real and imaginary parts of the CAF estimation can be written as follow

$$\hat{r}_{xx}^{\alpha}(\tau) = [Re\{\hat{R}_{xx}^{\alpha}(\tau)\}, Im\{\hat{R}_{xx}^{\alpha}(\tau)\}], \tag{10}$$

while $r_{xx}^{\alpha}(\tau) = [Re\{R_{xx}^{\alpha}(\tau)\}, Im\{R_{xx}^{\alpha}(\tau)\}]$ is the true row vector of the CAF.

In order to design a decision strategy for cyclic detector, the knowledge of the distribution of $(\hat{r}_{xx}^{\alpha}(\tau) - r_{xx}^{\alpha}(\tau))$ must be known. The distribution of $(\hat{r}_{xx}^{\alpha}(\tau) - r_{xx}^{\alpha}(\tau))$ is determined to assure the mean square sense (MSS) consistency of $\hat{R}_{xx}^{\alpha}(\tau)$ ($\lim_{T\to\infty} E[\mid \hat{R}_{xx}^{\alpha}(\tau) - R_{xx}^{\alpha}(\tau) \mid^2] = 0$) and the asymptotic complex normality (ACN) of $\sqrt{T}(\hat{R}_{xx}^{\alpha}(\tau) - R_{xx}^{\alpha}(\tau))$. By using mixing conditions i.e the MSS and ACN, it is known that $(\hat{r}_{xx}^{\alpha}(\tau) - r_{xx}^{\alpha}(\tau))$ is Gaussian distribution

$$\lim_{T\to\infty}\sqrt{T}(\hat{r}_{xx}^{\alpha}(\tau) - r_{xx}^{\alpha}(\tau)) \stackrel{D}{=} \mathcal{N}(0, \hat{\Sigma}_{rr}^{\alpha}(\tau)), \tag{11}$$

where $\stackrel{D}{=}$ denotes convergence in distribution, $\mathcal{N}$ stands for a multivariate normal density, and $\hat{\Sigma}_{rr}^{\alpha}(\tau)$ is the estimated covariance matrix of $r_{xx}^{\alpha}(\tau)$ [14].

$$\hat{\Sigma}_{rr}^{\alpha}(\tau) = \begin{bmatrix} Re\{\frac{\hat{S}_f + \hat{S}_f^{\star}}{2}\} & Im\{\frac{\hat{S}_f - \hat{S}_f^{\star}}{2}\} \\ Im\{\frac{\hat{S}_f + \hat{S}_f^{\star}}{2}\} & Re\{\frac{\hat{S}_f^{\star} - \hat{S}_f}{2}\} \end{bmatrix}, \tag{12}$$

where $\hat{S}_f$ and $\hat{S}_f^{\star}$ are the estimation of conjugate and non-conjugate cyclic spectrum of $f(t) = x(t)x^{\star}(t+\tau)$ which are

define as

$$\hat{S}_f = \frac{1}{TL} \sum_{s=-(L-1)/2}^{(L-1)/2} W(s) F_{T,\tau}(\alpha - \frac{s}{T}) F_{T,\tau}(\alpha + \frac{s}{T}), \tag{13}$$

$$\hat{S}_f^{\star} = \frac{1}{TL} \sum_{s=-(L-1)/2}^{(L-1)/2} W(s) F_{T,\tau}^{\star}(\alpha + \frac{s}{T}) F_{T,\tau}(\alpha + \frac{s}{T}), \tag{14}$$

where $W(s)$ is a spectral window of length L (odd) and $F_{T,\tau}(\alpha)$ is defined by

$$F_{T,\tau}(\alpha) = \sum_{t=0}^{T-1} f(t) e^{-j2\pi\alpha t}. \tag{15}$$

Based on ACN and a generalized likelihood ratio test (GLRT), the statistical cyclic test can be expressed as [14].

$$\mathcal{T}^{\alpha}(\tau) = T \hat{r}_{xx}^{\alpha}(\tau) \hat{\Sigma}_{rr}^{\alpha^{-1}}(\tau) \hat{r}_{xx}^{\alpha^T}(\tau), \tag{16}$$

Under hypothesis H_0, the $\mathcal{T}^{\alpha}(\tau)$ converges asymptotically to a central $\mathcal{X}^2$ distribution

$$\lim_{T\to\infty} \mathcal{T}^{\alpha}(\tau) \overset{D}{=} \mathcal{X}_2^2, \tag{17}$$

Under hypothesis H_1, the $\mathcal{T}^{\alpha}(\tau)$ converges asymptotically to normal distribution

$$\lim_{T\to\infty} \mathcal{T}^{\alpha}(\tau) \overset{D}{=} \mathcal{N}(T \hat{r}_{xx}^{\alpha}(\tau) \hat{\Sigma}_{rr}^{\alpha^{-1}}(\tau) \hat{r}_{xx}^{\alpha^T}(\tau), 4T \hat{r}_{xx}^{\alpha}(\tau) \hat{\Sigma}_{rr}^{\alpha^{-1}}(\tau) \hat{r}_{xx}^{\alpha^T}(\tau)). \tag{18}$$

For known cyclic frequency α, the conventional detection rule can be described as follow. For a fixed probability of false alarm rate $P_{FA} = Pr\{\mathcal{T}^{\alpha}(\tau) \geqq \gamma \mid H_0\}$, the threshold γ can be determined as

$$\gamma_{sc} = Q_{\mathcal{X}_2^2}^{-1}(P_{FA}). \tag{19}$$

Then, the probability of detection P_D can be expressed as

$$P_D = Q\left(\frac{\gamma_{sc} - T \hat{r}_{xx}^{\alpha}(\tau) \hat{\Sigma}_{rr}^{\alpha^{-1}}(\tau) \hat{r}_{xx}^{\alpha^T}(\tau)}{\sqrt{4T \hat{r}_{xx}^{\alpha}(\tau) \hat{\Sigma}_{rr}^{\alpha^{-1}}(\tau) \hat{r}_{xx}^{\alpha^T}(\tau)}} \right). \tag{20}$$

3. Cooperative Sensing Techniques

3.1 Cooperative Sensing Based on Energy Detection

The hypothesis test for the conventional energy detection can be expressed as in Equation (6) and (7). It is commonly seen that the conventional statistical test for energy detection is written as

$$\mathcal{T} = \sum_{t=0}^{T-1} x(t) x^{\star}(t). \tag{21}$$

However, the hypothesis test for N_u users in the case of cooperative sensing (CS) can be presented as

$$H_0 : x_u(t) = w_u(t), \qquad \text{signal is absent} \tag{22}$$

$$H_1 : x_u(t) = s_u(t) + w_u(t), \qquad \text{signal is present} \tag{23}$$

where $u = 1, 2, ...N$. The statistical test for the cooperative sensing can be expressed as follows

$$\mathcal{Z}_{ed} = \sum_{u=1}^{N_u} \sum_{t=0}^{T-1} x_u(t) x_u^{\star}(t). \tag{24}$$

In [15], it has been shown that under hypothesis H_0 the $\mathcal{Z}_{ed}$ converges to

$$\lim_{T\to\infty} \mathcal{Z}_{ed} = \mathcal{N}(T \sum_{u=1}^{N_u} \sigma_{w,u}^2, 2T \sum_{u=1}^{N_u} \sigma_{w,u}^4), \tag{25}$$

and under hypothesis H_1,

$$\lim_{T\to\infty} \mathcal{Z}_{ed} = \mathcal{N}(T \sum_{u=1}^{N_u} (\sigma_{s,u}^2 + \sigma_{w,u}^2), 2T \sum_{u=1}^{N_u} (\sigma_{s,u}^2 + \sigma_{w,u}^2)^2), \tag{26}$$

where σ_w^2 and σ_s^2 are the variance of noise and signal, respectively.

3.2 Cooperative Sensing Based on Cyclic Detection

Cooperative sensing based on cyclic detection implies that the secondary users share their decision statistical test about the presence or absence of the primary signals with other secondary users. Similar to cooperative sensing based on energy detection, the statistical cyclic test for cooperative sensing based on cyclic detector can be expressed as follows

$$Z_{cs} = \sum_{i=1}^{N_{\alpha}} \sum_{u=1}^{N_u} \mathcal{T}_u^{\alpha_i}(\tau). \tag{27}$$

N_u is the total number of secondary users while N_{α} is the total number of cyclic frequencies in the set of $\mathcal{P}$ and $\mathcal{T}_u^{\alpha}(\tau)$ is the statistical tests from u^{th} secondary user. We assume that the secondary users are independent to each other on deciding whether or not the hypothesis H_0 or H_1 is true. The statistical test Z_{cs} under hypothesis test H_0 can be expressed as follow

$$Z_{cs} = \mathcal{X}_{2N_{\alpha}N_u}^2, \tag{28}$$

and under hypothesis test H_1, it can be expressed as

$$Z_{cs} \overset{D}{=} \mathcal{N}(\mathcal{M}_{cs}^{\alpha}(\tau), \mathcal{V}_{cs}^{\alpha}(\tau)), \tag{29}$$

where $\mathcal{M}_{cs}^{\alpha}(\tau)$ is given by

$$\mathcal{M}_{cs}^{\alpha}(\tau) = \sum_{i=1}^{N_{\alpha}} \sum_{u=1}^{N_u} (T \hat{r}_{xx}^{\alpha_i}(\tau, u) \hat{\Sigma}_{rr}^{\alpha_i^{-1}}(\tau, u) \hat{r}_{xx}^{\alpha_i^T}(\tau, u)) \tag{30}$$

and the $\mathcal{V}_{cs}^{\alpha}(\tau)$ is given by

$$\mathcal{V}_{cs}^{\alpha}(\tau) = \sum_{i=1}^{N_{\alpha}} \sum_{u=1}^{N_u} (4T \hat{r}_{xx}^{\alpha_i}(\tau, u) \hat{\Sigma}_{rr}^{\alpha_i^{-1}}(\tau, u) \hat{r}_{xx}^{\alpha_i^T}(\tau, u)) \tag{31}$$

For a given P_{FA}, the threshold γ can be determined as

$$\gamma_{cs} = Q^{-1}_{\chi^2_{2N_\alpha N_u}}(P_{FA}) \tag{32}$$

and the P_D is therefore given by

$$P_D = Q\left(\frac{\gamma_{cs} - \mathcal{M}^\alpha_{cs}(\tau)}{\sqrt{\mathcal{V}^\alpha_{cs}(\tau)}}\right) \tag{33}$$

4. Simulation Results

Table 1 shows the parameters of the primary system (ISDB-T system in mode 1). The ISDB-T system basically comprises of 13 OFDM segments for wideband and 1 or 3 OFDM segments for narrow band. The ISDB-T system operates in the frequency bands from 470 MHz to 770 MHz.

4.1 CAF Simulation

The estimation of cyclic auto correlation function $\hat{R}^\alpha_{xx}(\tau)$ (8) is computed via FFT. Fig. 1(a) shows the magnitude of the $\hat{R}^\alpha_{xx}(\tau)$ with sensing time $T = 6.3$ ms and the delay $\tau = T_u$. As depicted in Fig. 1(a), the $\hat{R}^\alpha_{xx}(\tau)$ shows several peaks indicating the possibility of the presence of several cyclic frequencies. However, it is not clear how to decide which one is the cyclic frequency and which one is not since $\hat{R}^\alpha_{xx}(\tau)$ is non zero for almost all given α. To overcome this problem, the statistical test (16) is investigated. From the available data $x(t)$ and using (8), compute the row vector (10) which contains the $\hat{R}^\alpha_{xx}(\tau)$. Then, fill in the entries of the estimated auto covariance matrix $\hat{\Sigma}^\alpha_{rr}(\tau)$ (12) using (13) and (14). The statistical test can be obtained by substituting equation (10) and (12) in (16). In this simulation, $F_{T,\tau}(\alpha)$ is computed by using FFT with sensing time $T = 6.3$ ms and the delay $\tau = T_u$, while equations (13) and (14) are computed by using a Kaiser window of parameter 10 and length $L = 601$. Fig. 1(b) shows the test statistic (16) along with the threshold corresponding to $P_{FA} = 1\%$. It can be clearly seen that the cyclic frequencies are multiple of $1/T_s$ as expected. However, some cyclic frequencies can not be recognized since they are lower than the threshold (dashed line).

4.2 Performance of Cooperative Sensing Based on Cyclic Detector

In this section, the performance gain from the cooperative sensing of several secondary users is evaluated. The aim of this evaluation is to demonstrate the influence of SNR difference among the cooperative secondary users. Fig. 2 depicts the detection performance for multiple users for the single and multiple cyclic frequencies. In this simulation, the statistical test is the same as above and the $P_{FA} = 1\%$. Each secondary user receives the same signal with different noise but with same SNR for each secondary users. From figure 2, it is seen that the detection performance is improved as the number of cooperative users is increased.

Table 1 OFDM signal of ISDB-T

Parameter	Description
QPSK	QPSK modulation
$T_u = 252\ \mu$s	OFDM useful symbol duration
$T_g = T_u/4$	OFDM guard interval
$T_s = T_u + T_g$	OFDM total symbol duration
$N_s = 20$	Number of OFDM symbols (= 6.3 ms)
$N_c = 1406$	Number of sub-carriers
$\Delta f = 3.968$ kHz	Carrier separation (= $1/T_u$)
$f_s = 16.25$ MHz	Sampling frequency

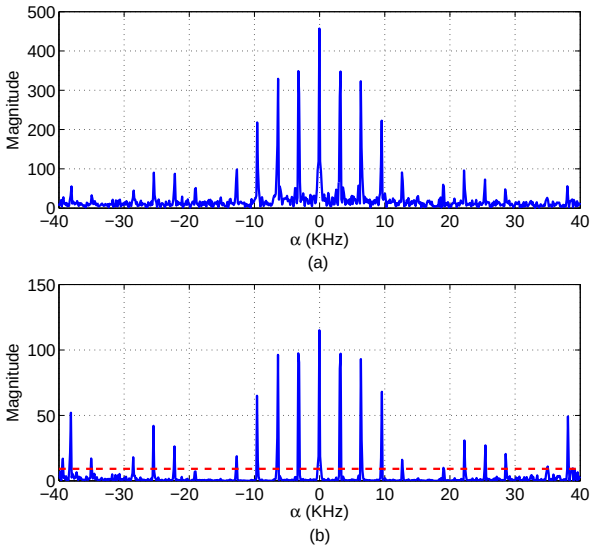


Figure 1 Candidate cyclic frequencies: (a) CAF estimation $\hat{R}^\alpha_{xx}(\tau)$, (b) Test statistic $\mathcal{T}^\alpha(\tau)$

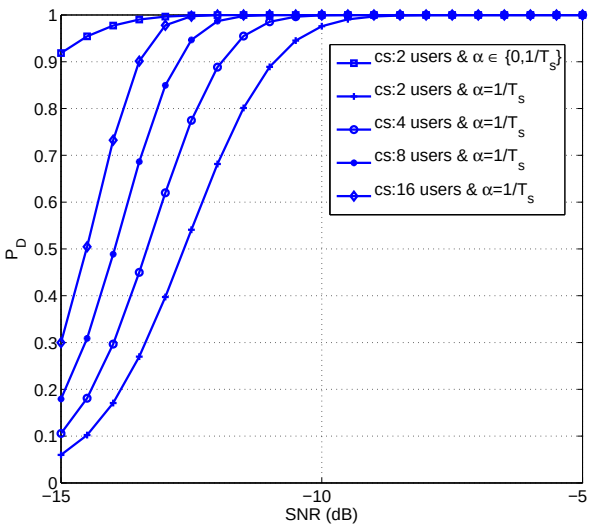


Figure 2 P_D vs. SNR in CS with $P_{FA} = 1\%$

4.3 Performance Comparison of Cooperative Sensing between Energy and Cyclic Detector

Fig. 3 depicts the detection performance between the co-

operative sensing based on energy and cyclic detector. In this case, the statistical test is the same as above and the $P_{FA} = 1\%$. Each secondary user receives the same signal with different noise and SNR is the same for each users. Fig. 3 shows that the cyclic detector outperforms the energy detector at low SNR. For example, focussing on 2 users, the probability of detection based on energy detector is seen to rapidly approach 1 when $SNR = -10$ dB while the probability of detection based on cyclic detector is seen to rapidly approach 1 when $SNR = -13$ dB. Performance gain of roughly 3 dB is obtained from the cooperative based on cyclic detection.

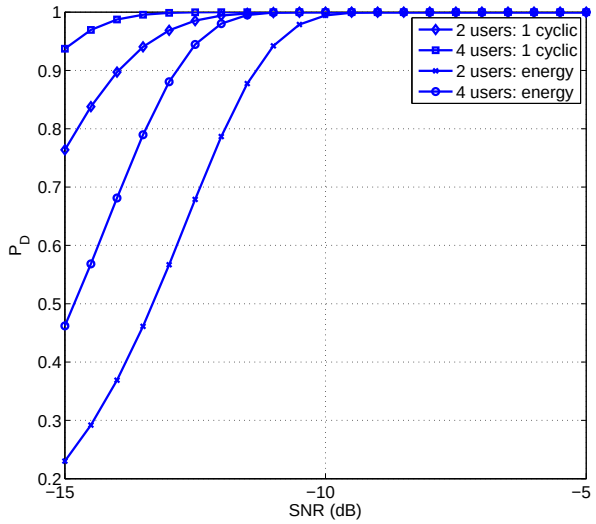


Figure 3 P_D vs. SNR in CS between energy and cyclic detection with $P_{FA} = 1\%$

5. Conclusion

In this paper, the detection performances of cyclic detector and energy detector based on cooperative sensing from multiple secondary users are investigated. Through the simulation results, it is confirmed that both cyclic detector and energy detector based on cooperative sensing method outperforms at low SNR. In comparison, the detection performances between the cooperative sensing based on energy detection and cyclic detection have indicated the significant gains of detection performance obtained via the collaboration between the secondary users. The detection performance of cyclic detector is better than the energy detector.

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