Performance of Energy Detection Spectrum Sensing with Delay Diversity for Cognitive Radio System

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Abstract

In this paper, a new spectrum sensing method based on energy detection is proposed and analyzed in a cognitive radio(CR) system. We employ a delay diversity receiver for sensing the primary user's spectrum with reasonable cost and complexity. Conventional CR with the receiver equipping multiple antennas requires additional hardware and space for installing multiple antennas in accordance with increase in the number of antennas. If the number of antennas increases, detection probability as well as hardware complexity and cost rise. Then, it is difficult to make a primary user detector practically. Therefore, we adopt a delay diversity receiver for solving problems of the conventional spectrum detector utilizing multiple antennas. We derive analytical expressions for the spectrum sensing performance of the proposed system. From the simulation results, it is demonstrated that the primary user detector with the delay diversity receiver has almost half the complexity and shows similar or improved performance as compared with that employing multiple antennas. Therefore, the proposed spectrum sensing structure can be a practical solution for enhancing the detection capacity in CR system operations. The results of this paper can be applied to legacy CR systems with simple modifications.

Key words : Cognitive Radio(CR), Delay Diversity, Energy Detection, Multiple Antennas, Receiver Complexity, Spectrum Sensing.

Ⅰ. Introduction

In accordance with the growth of wireless communication technologies, the demand for radio-frequency spectrum resources is increasing in order to satisfy user needs. However, spectrum is inherently a limited natural resource. Therefore, the spectrum scarcity problem can occur. In the current spectrum regulatory framework, frequency bands are statically assigned to specific services. Also, unlicensed users cannot make use of the spectrum resources that are already allocated to the licensed users.

A recent survey report for spectrum utilization, which is published by the Spectrum Policy Task Force(SPTF) within the Federal Communications Commission(FCC), has indicated that most of the actual licensed spectrum bands are under-utilized in vast temporal and geographic dimensions[1]. In [2], it has been indicated that the maximum total spectrum occupancy is 13.1 % from 30 MHz to 3 GHz in New York City and less than 35 % below 3 GHz in Washington, D.C. Also, for as much as 90 % of the time, large portions of the licensed bands remain unused.

Then, cognitive radio(CR)[3], which is the advanced scheme of software-defined radio(SDR)[4], has been proposed in order to improve the efficiency of spectrum resource utilization. CR has three basic functions. One is to sense the surrounding environment. Another is to learn in both supervised and unsupervised modes. The other is to adapt within any layer of the radio communication system by making corresponding changes in certain operating parameters, which are as follows: transmission of power, carrier frequency, and modulation strategy[5]. Therefore, by employing CR technology, we can sense, manage, share, and change the spectrum resources[6],[7]. Spectrum sensing is used to determine which portions of the spectrum are available and to detect the presence of licensed users when a user operates in a licensed band. Spectrum management is to select the best available channel. Spectrum sharing is to coordinate access to the channel with other users. Spectrum mobility is to vacate the channel when a licensed user is detected. Among these functions, spectrum sensing is an essential and fundamental requirement for the development of CR systems, as it enables CR to adapt to its environment by detecting the unused spectrum resources, which are known as spectrum holes.

There are several spectrum sensing techniques, such as matched filter detection, energy detection, cyclosta-

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tionary feature detection, wavelet detection, and covariance detection[8]~[14]. And there are cooperative techniques for increasing the probability of detection in fading channels[15]~[17]. In cooperative spectrum sensing, local spectrum sensing results from several CR users are transmitted to the fusion center and combined for detecting a primary user(PU). Wireless channels between the PU and CR users are normally assumed to be a Rayleigh fading channel with additive white Gaussian noise(AWGN). But the channels between the CR users and fusion center are assumed to be a perfect channel[18]~[21].

In other words, the transmitted signals from the CR user are the same as the signals received at the fusion center. However, since the links between the CR users and fusion center are also wireless channels where interfering signals and noise exist, it is impossible for the fusion center to receive the local sensing results from several CR users without any error. In [22], the spectrum sensing performance is analyzed in a realistic environment where the radio channels between the CR users and fusion center are characterized by Rayleigh fading channels. And in order to further improve the spectrum sensing performance and achieve reliable detection over wireless multipath fading channels, multiple antennas are adopted in [23] and [24]. Since spectrum sensing with multiple antennas performs pre-detection combining while cooperative spectrum sensing only allows post-detection combining, the former outperforms the latter under the same conditions such as the number of branches and the correlation among branches.

Although it has been shown that the spectrum sensing performance improves as the number of antennas increases, the CR user with multiple antennas also requires additional cost associated with antenna elements and strict zoning requirements. In order to overcome those shortcomings of the system with multiple antennas, the delay diversity receiver has been proposed and analyzed for synchronous CDMA channels in [25] and [26]. This receiver can achieve the performance enhancements of the polarization and spatial diversity receiver, but with about half the complexity for the same diversity order.

With this motivation, we propose the spectrum sensing scheme with the delay diversity receiver and derive analytical expressions for the performance of the proposed CR system. We can expect that the CR system with the delay diversity receiver can increase the detection performance with low cost and complexity. In general, the energy detection method is often used for sensing the PU's spectrum because it is simple, and the CR user does not have the knowledge about the signal to detect. Therefore, we employ the energy detection method for sensing the spectrum.

The remainder of this paper is organized as follows. In Section Ⅱ, the proposed CR system with the delay diversity receiver is described and compared with the conventional CR system with multiple antennas. In order to analyze the performance, the statistics of the decision variables and the expressions for the detection probability and false-alarm probability are derived in Section Ⅲ. In Section Ⅳ, simulation results for the proposed system are presented. Finally, concluding remarks are provided in Section Ⅴ.

Ⅱ. System Models

2-1 Conventional CR System with Multiple Antennas

In Fig. 1, the block diagram for the conventional CR system with multiple antennas is shown. This conventional system is composed of N receive antennas, N signal processing parts, N local decision parts, and one global decision part. In order to guarantee that the signals between each pair of receiver antennas fade independently, each receiver antenna is sufficiently separated in space. At each antenna element, a received signal is converted into a baseband signal through RF and IF Circuit block. And the resulting signal is converted into a digital signal through an analog-to-digital converter. Signal characteristics, such as a period, are detected at a Power/Feature Measurement block. Then, a local decision is made based on the detected characteristic. In order to make an efficient and reliable decision as to whether a primary user is occupying the spectrum band assigned to him, a global decision is made by using local decision results from N antenna elements.

The conventional CR system with multiple antennas achieves a performance improvement in spectrum sensing accordingly as the number of antenna elements increases. However, the system complexity rises in proportion to increase in the number of antenna elements. Therefore, we can expect that the cost of the CR system rises, too.

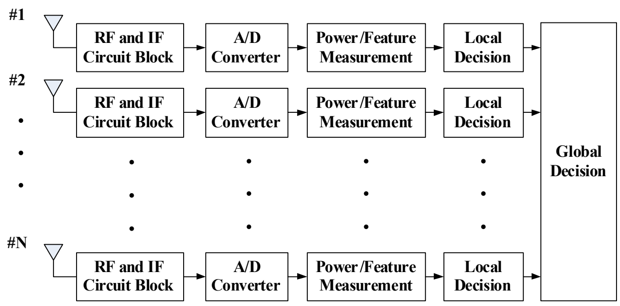

Fig. 1. Conventional CR system structure with multiple antennas.

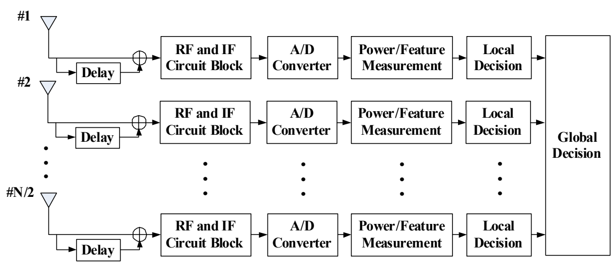

Fig. 2. Proposed CR system structure with delay diversity receiver.

2-2 Proposed CR System with Delay Diversity Receiver

In this paper, we propose a CR system that can enhance the spectrum sensing performance with low cost and complexity. Fig. 2 shows the proposed CR system with the delay diversity receiver. The proposed system is composed of $N/2$ receive antennas, $N/2$ delay elements, $N/2$ signal processing parts, $N/2$ local decision parts, and one global decision part. One antenna element is composed of a normal branch and a delay branch. The radio frequency(RF) signal received from one antenna element is intentionally delayed by a pre-determined amount at the delay branch and added to the next RF signal of the normal branch, which is received from the same antenna element. In order to guarantee independence of the fading statistics and avoid overlap between the delayed and normal signals, the pre-determined intentional delay needs to be larger than the maximum excess path delay of the meaningful multipath signals from the normal branches.

In this case, it is assumed that N is an even number. The proposed CR system has $N/2$ normal branches and $N/2$ delay branches. Therefore, it has a total of N branches. The proposed CR system can be easily applied to the conventional CR system with some modification of the antenna subsystem and does not require additional hardware units or space unlike the CR system in Fig. 1.

The main point of the proposed CR system with the delay diversity receiver is to achieve the performance enhancement of the CR system with N multiple antennas, but with about half the complexity for the same diversity order. Both the conventional and proposed CR systems utilize N physical antenna elements as the diversity source. But the delay diversity receiver requires only a half number of RF, IF, and sensing modules through the signals at the RF level with intentional delays.

Ⅲ. Performance Analysis

In this section, the detection probability, false-alarm rate, and miss detection probability are derived for each type of CR system. In the performance analysis, the following assumptions are made for simplicity of analysis: 1) all the signals from antenna elements are independent; 2) the wireless channel is the Gaussian channel; 3) local decision results are combined with an equal gain combining(EGC) scheme.

3-1 Conventional CR System with Multiple Antennas

If the hypothesis H_0 represents the case where the PU is not in the frequency band of interest, and the H_1 represents the case where the PU is in the band, the signal detection problem can be modelled by a simple binary hypothesis-testing problem as follows[27]~[29].

$$\begin{cases} H_0: \; y_n[k] = n_n[k] \\ H_1: \; y_n[k] = h_n[k] \otimes x[k] + n_n[k] \end{cases}, \tag{1}$$

where $k=1,2,\cdots,K$, $n=1,2,\cdots,N$, $y_n[k]$ is a received signal at the n^{th} antenna of the CR system, $h_n[k]$ is an impulse response of the channel between the PU and the n^{th} antenna of the CR system, $x[k]$ is a transmitted signal from the PU, and $n_n[k]$ is AWGN with zero mean and variance σ_N^2. And K denotes the number of samples.

In order to detect the PU, the energy detection method is employed in this paper. The energy of the received signal at the n^{th} antenna of the CR system, $E_n[k]$, can be expressed as

$$E_n[k] = |y_n[k]|^2. \tag{2}$$

And in order to judge whether the PU exists or not in the assigned frequency band, $E_n[k]$ is compared with a predetermined threshold of the n^{th} antenna, γ_n, which is determined according to a false-alarm probability. Hence, a local decision result of the n^{th} antenna elements, $D_n[k]$, can be expressed as

$$D_n[k] = H(E_n[k] - \gamma_n), \tag{3}$$

where $H(\cdot)$ represents the Heaviside step function. In other words, if $E_n[k]$ is more than or equal to γ_n, the local decision result is $D_n[k]=1$. And if $E_n[k]$ is less than γ_n, $D_n[k]=0$. Then, for making a global decision, N local decision results are combined and compared with a predetermined threshold γ, which is determined in accordance with a decision rule. A global decision, $D[k]$, is calculated as

$$D[k] = H\left(\frac{1}{N}\sum_{n=1}^{N} D_n[k] - \gamma\right). \tag{4}$$

If $D[k]=1$, the PU is in the frequency band. Therefore, the CR user cannot use the spectrum. However, if

$D[k]=0$, the primary user is not using the frequency band. Then, the CR user has the right to utilize the spectrum. There are several decision rules[30,31], which are AND, OR, and MAJORITY rules. If the values of γ are $1/N$, 1, and $N/2$, the decision rules are called AND, OR, and MAJORITY rules, respectively. In an AND rule, one of $D_n[k]$ is "0", and the global decision is made as the PU is absent. In an OR rule, one of $D_n[k]$ is "1", and the global decision is made as the PU is present. In a MAJORITY rule, the global decision is made by a majority of $D_n[k]$.

The probability density functions(PDFs) of the received signal at the n^{th} antenna, $y_n[k]$, for H_0 and H_1 cells can be expressed as (5) and (6), respectively.

$$f_Y(y\ H_0)=\frac{1}{\sqrt{2\pi\sigma_N^2}}\exp\left(-\frac{y^2}{2\sigma_N^2}\right), \tag{5}$$

$$f_Y(y\ H_1)=\frac{1}{\sqrt{2\pi\sigma_N^2}}\exp\left(-\frac{(y-\mu_x)^2}{2\sigma_N^2}\right), \tag{6}$$

where μ_x is a mean value of $x[k]$. After the local decisions, the decision variable $V[k]$ used for the global decision can be expressed as

$$V[k]=\sum_{n=1}^{N} D_n[k]. \tag{7}$$

Hence, the PDFs of $V[k]$ for H_0 and H_1 cells can be expressed as (8) and (9), respectively.

$$f_V(v\ H_0)=\frac{1}{\sqrt{2\pi\sigma_V^2}}\exp\left(-\frac{v^2}{2\sigma_V^2}\right), \tag{8}$$

$$f_V(v\ H_1)=\frac{1}{\sqrt{2\pi\sigma_V^2}}\exp\left(-\frac{(v-\mu_V)^2}{2\sigma_V^2}\right), \tag{9}$$

where $\mu_V=\frac{1}{N}\sum_{n=1}^{N} D_n[k]$ and $\sigma_V^2=\frac{1}{N}\sum_{n=1}^{N} D_n^2[k]-\mu_V^2$.

The detection probability for a given value of the decision threshold is defined as the probability of the event that the decision variable $V[k]$ corresponding to an H_1 cell exceeds the decision threshold γ, which can be obtained by

$$P_D=\int_{\gamma}^{\infty} f_V(v\ H_1)dv \tag{10}$$

where P_D represents the detection probability of an H_1 cell. Upon substituting (9) into the above equation, it can be derived after some algebra that

$$P_D=\int_{\gamma}^{\infty}\frac{1}{\sqrt{2\pi\sigma_V^2}}\exp\left(-\frac{(v-\mu_V)^2}{2\sigma_V^2}\right)dv. \tag{11}$$

Letting $z=\frac{v-\mu_V}{\sigma_V}$, then (11) can be rewritten as

$$P_D=\int_{\frac{\gamma-\mu_V}{\sigma_V}}^{\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{z^2}{2}\right)dz=Q\left(\frac{\gamma-\mu_V}{\sigma_V}\right), \tag{12}$$

where $Q(\cdot)$ is a standard normal complementary cumulative distribution function(CDF)[32]~[34].

The threshold value is determined from the false-alarm probability, P_{FA}, associated with an H_0 cell. The false-alarm probability is defined as the probability of the event that the output decision variable corresponding to an H_0 cell exceeds the decision threshold, which can be expressed as

$$P_{FA}=\int_{\gamma}^{\infty} f_V(v\ H_0)dv. \tag{13}$$

Upon substituting (8) into (13) and performing the required integrations, the false-alarm probability is obtained by

$$P_{FA}=\int_{\gamma}^{\infty}\frac{1}{\sqrt{2\pi\sigma_V^2}}\exp\left(-\frac{v^2}{2\sigma_V^2}\right)dv. \tag{14}$$

By letting $z=\frac{v}{\sigma_V}$, then (14) can be rewritten as

$$P_{FA}=\int_{\frac{\gamma}{\sigma_V}}^{\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{z^2}{2}\right)dz=Q\left(\frac{\gamma}{\sigma_V}\right). \tag{15}$$

3-2 Proposed CR System with Delay Diversity Receiver

At each antenna element, there are two kinds of signals. One is from the normal branch and the other is from the delay branch. Therefore, the combined signal at the n^{th} antenna of the CR system can be expressed as

$$\begin{cases} H_0:\ y_n[k]=n_T[k] \\ H_1:\ y_n[k]=h_n[k]\otimes x[k] \\ \quad +h_n[k-\tau]\otimes x[k-\tau]+n_T[k], \end{cases} \tag{16}$$

where $k=1,2,\ldots,K$, τ is the predetermined delay value and $n_T[k]$ is the sum of AWGN from the normal and delay branches with zero mean and variance σ_T^2.

The energy of the received signal at the n^{th} antenna branch of the CR system can be expressed in (2). However, a local decision result of the n^{th} antenna elements, $D_n[k]$, can be expressed as

$$D_n[k]=H\left(\frac{1}{2}E_n[k]-\gamma_n\right). \tag{17}$$

And the global decision can be calculated as

$$D[k]=H\left(\frac{1}{N/2}\sum_{n=1}^{N/2} D_n[k]-\gamma\right). \tag{18}$$

When there are H_0 and H_1 cells, the PDFs of $y_n[k]$ can be expressed as follows.

$$f_Y(y\ H_0)=\frac{1}{\sqrt{2\pi\sigma_T^2}}\exp\left(-\frac{y^2}{2\sigma_T^2}\right), \tag{19}$$

$$f_Y(y\ H_1)=\frac{1}{\sqrt{2\pi\sigma_T^2}}\exp\left(-\frac{(y-\mu_T)^2}{2\sigma_T^2}\right), \tag{20}$$

where $\mu_T = \mu_{N,Normal} + \mu_{N,Delay}$ and $\sigma_T^2 = \sigma^2_{N,Normal} + \sigma^2_{N,Delay}$. $\mu_{N,Normal}$ and $\mu_{N,Delay}$ are mean values of the received signal at the normal and delay branches, respectively. $\sigma^2_{N,Normal}$ and $\sigma^2_{N,Delay}$ are variances of the received signal at the normal and delay branches, respectively.

After the local decisions, the decision variable $V[k]$ can be expressed as

$$V[k] = \sum_{n=1}^{N/2} D_n[k]. \tag{21}$$

Hence, the PDFs of $V[k]$ when H_0 and H_1 cells are tested are given by

$$f_V(v|H_0) = \frac{1}{\sqrt{2\pi\sigma_V^2}} \exp\left(-\frac{v^2}{2\sigma_V^2}\right), \tag{22}$$

$$f_V(v|H_1) = \frac{1}{\sqrt{2\pi\sigma_V^2}} \exp\left(-\frac{(v-\mu_V)^2}{2\sigma_V^2}\right), \tag{23}$$

where $\mu_V = \frac{1}{N/2}\sum_{n=1}^{N/2} D_n[k]$ and $\sigma_V^2 = \frac{1}{N/2}\sum_{n=1}^{N/2} D_n^2[k] - \mu_V^2$.

The PDFs of the decision variable $V[k]$ in (22) and (23) are similar to those of the conventional CR system except for the forms of mean and variance. So measures of the system performance can be expressed as (12) and (15).

Ⅳ. Simulation Results

In this section, the spectrum sensing performance of the proposed system employing the delay diversity receiver is evaluated and compared with that of the conventional system. In order to verify the performance of the proposed system, its detection probability is tested for a pre-specified false-alarm probability at a given signal-to-noise ratio(SNR), various system parameters, and different decision rules. We consider 1, 2, 4, and 8 multiple-antenna systems. Also, we consider the proposed system with 1, 2, and 4 antennas. The PU's signal is a binary phase shift keying(BPSK) signal. The wireless channel is assumed to be an AWGN channel. And the false-alarm probability is set at 1 %.

Fig. 3 shows the detection probability performance with varying SNR for the proposed CR system employing the delay diversity receiver when the AND decision rule is applied. It is shown that the detection probability decreases as the number of antennas increases. The reason for this is that the global decision result is "0" if one of the local decision results is "0". Therefore, in accordance with the increase of the number of antennas, the probability that all local decision results are "Detection "decreases, and the detection probability of the

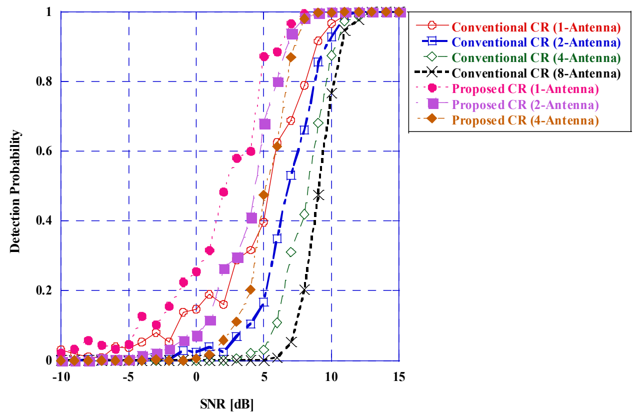

Fig. 3. Detection probability of the proposed system for AND decision rule.

global decision also decreases. The proposed CR system achieves remarkable spectrum sensing performance over the conventional one for comparable complexity. The cases of 8, 4, and 2 antennas for the conventional CR system are identical to those of 4, 2, and 1 antenna for the proposed CR system on the basis of the number of received signal paths. For the detection probability of 0.6, the gap of the required SNR between the proposed CR system with 2 antennas and the conventional one with 4 antennas is about 4 dB. This means that the received power level of the conventional CR system with 4 antennas needs to be 4 dB larger than that of the proposed one with 2 antennas in order to achieve the same spectrum sensing performance at the same level of AWGN. In the cases of both the same number of the received signal paths and the same number of the antennas, the detection probability of the proposed CR system is higher than that of the conventional one at a similar or half the cost and complexity. The saved resources can be used to enhance the capacity of the CR system.

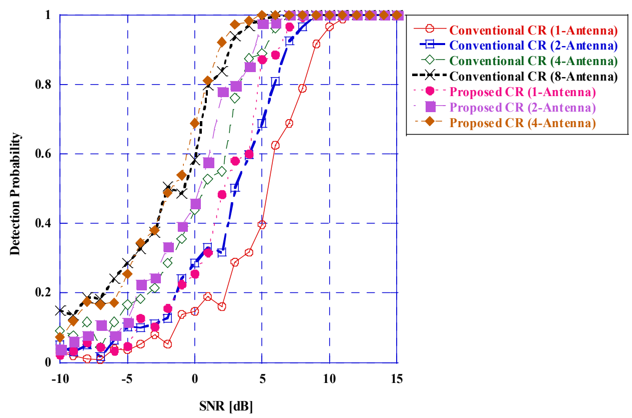

Fig. 4. Detection probability of the proposed system for OR decision rule.

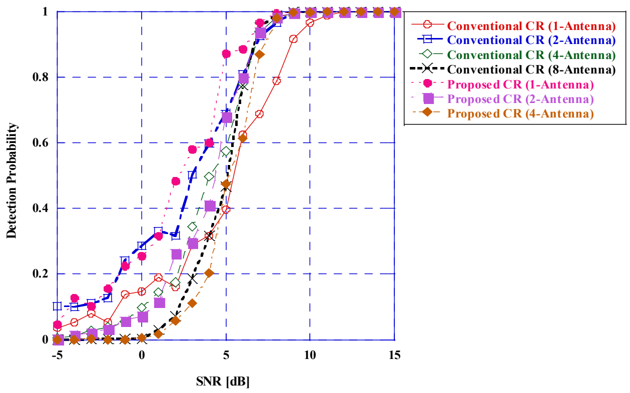

Fig. 5. Detection probability of the proposed system for MAJORITY decision rule.

In Fig. 4, comparisons of the detection probability for the proposed CR system against the conventional CR system are shown when the OR decision rule is used. It is shown that as the number of antennas increases, the detection probability decreases. This is because the global decision result is "1" if one of the local decision results is "1". Therefore, the probability that all local decision results are "Miss Detection" decreases, and the detection probability of the global decision increases according to increase the number of antennas. When the number of antennas is the same, the sensing performance of the proposed CR system is better than the conventional one is. However, if the number of the received signal paths is identical, there seldom exists a difference in the detection probability. From the results, the spectrum sensing performance is considerably enhanced by adding delay units to the CR system with multiple antennas. Besides, when the number of the received signal paths is identical, the CR system with the delay diversity receiver has low complexity and shows a similar or superior detection performance to that with multiple antennas.

In Fig. 5, the detection probability performance of the proposed system is presented when the MAJORITY decision rule is utilized. When the number of the received signal paths is identical, two systems show similar spectrum sensing performances. However, the conventional CR system requires high cost and considerable complexity. Therefore, we can reduce the cost and complexity of the CR system by employing the delay diversity receiver for achieving similar performance.

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Ⅴ. Conclusions

In this paper, we proposed and evaluated the spectrum sensing method with the delay diversity receiver for enhancing the detection performance without the increase in cost and complexity. In the conventional CR system with multiple antennas, not only spectrum sensing performance but also cost and system complexity increased as the number of antennas increased. Therefore, it was difficult to implement the practical CR system equipping multiple antennas. However, with almost half the complexity, the proposed CR system could achieve similar or higher performance than the conventional CR system did. In other words, the spectrum sensing performance was considerably enhanced by adding delay units to the CR system with reasonable cost and complexity. The proposed CR system is expected to provide a practical solution for improving the spectrum sensing capacity. Of course, some additional time is required due to delay.

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