Improving Spectrum Sensing and Reporting via Multi-Antenna in Cognitive Radio Networks

Muhammad Sajjad Khan
Department of Electrical Engineering,
International Islamic University, Islamabad, Pakistan
sajjad.khan@iiu.edu.pk

Mi Ji Kim
Department of Electronics Engineering,
Korea Polytechnic University,
S. Korea
mijikim@kpu.ac.kr

Junsu Kim
Department of Electronics Engineering,
Korea Polytechnic University,
S. Korea.
junsukim@kpu.ac.kr

Eung Hyuk Lee
Department of Electronics Engineering,
Korea Polytechnic University,
S. Korea.
eshlee@kpu.ac.kr

Su Min Kim*
Department of Electronics Engineering,
Korea Polytechnic University,
S. Korea.
suminkim@kpu.ac.kr

***Abstract*—Spectrum sensing is a vital functionality of cognitive radio network to identify an available spectrum for secondary users to enhance spectrum utilization and to avoid harmful interference to licensed users. However, the performance of spectrum sensing is highly degraded due to fading and hidden terminal issues. Recent development in multi-antenna techniques provides a new dimension to spectrum sensing. In this paper, we propose a multi-antenna based signal detection scheme in multi-band systems. We consider an ordered sequential data fusion scheme i.e., Dempster-Shafer (D-S) evidence theory, which increases system reliability. Also, an ordered sequential reporting mechanism is proposed for multi-antenna based systems to enhance the system performance by reducing reporting time duration. The effectiveness of the proposed scheme is demonstrated through simulations, compared with existing schemes.**

Keywords—Cognitive radio; data fusion center; Dempster-Shafer(D-S) theory; multi-antenna; multi-band; ordered sequential reporting.

I. INTRODUCTION

In wireless communications, quality of service (QoS) and reliability of data play a vital role in system performance and should be considered as a priority [1,2]. The main objective in wireless communication is to utilize spectrum efficiently with reduced energy consumption and communication overhead, [3, 4]. The rapid growth of the wireless communication applications has raised demand of the spectrum bands. Due to fixed spectrum allocations, an issue of the spectrum scarcity has been further complex and demanding, because some of the spectrum bands is heavily utilized, while other spectrum bands are weakly utilized. According to the Federal Communication Commission (FCC), the temporal and geographical variations in the utilization of the assigned spectrum varies from 15% to 85% [5].

The spectrum scarcity can be overcome by using dynamic spectrum access (DSA) [6]. In the DSA, cognitive radio network (CRN) is one of promising candidates to efficiently utilize the spectrum by allowing cognitive users to access and utilize the spectrum opportunistically [7,8]. A main challenge in CRN is spectrum sensing that identifies the existence of licensed users (LUs) in the network and whenever LU is detected, secondary users (SUs) need to vacate the spectrum. Thus, the way how to perform the spectrum sensing is a crucial task [9].

The performance of conventional single node spectrum sensing degrades due to multi-path fading and hidden terminal problem. Outstanding performance can be obtained by cooperative spectrum sensing (CSS) over a single node sensing method [10]. In the CSS, each SU makes a local decision and sends it to a fusion center (FC) for final decision. Various fusion rules are utilized at the FC such as AND, OR, majority rule, etc. Unlike the conventional CSS, the system performance is significantly improved with a data fusion scheme which is based on Dempster-Shafer (D-S) evidence theory without prior knowledge of the LU [11]. Moreover, the concept of multi-antenna system has drawn a lot of interests in CR research, which overcomes the problems of fading and hidden terminal whereas the effect of the multi-path fading is effectively converted into benefit. Thus, the combination of the multiple antennas with multiple SUs can achieve the outstanding performance in detection of the LU, compared to the conventional CCS.

A number of studies have investigated multiple antennas from various points of view in different areas of research [12-14]. In [15], the authors analytically studied the performance of multiple antennas in CSS. In [16], the authors considered the performance of multiple antennas with the correlation factor among the multiple antennas. The weights for the multiple antennas were quantified and measured in [17]. However, all the above works either considered the conventional decision rules or a single energy detector. If the energy detector fails to perform in any scenario, the system performance is highly degraded.

In this paper, we propose a spectrum sensing scheme using multiple antennas based on D-S evidence theory with multi-band over Rayleigh fading channels. Also, we propose an ordered sequential reporting mechanism for multiple antennas with multiple bands. Through extensive simulations, we verify that the proposed multi-antenna with multi-band cooperative spectrum sensing based on D-S evidence theory improves the spectrum performance. Moreover, the proposed reporting mechanism significantly reduces the required reporting time.

The remaining of the paper is organized as follows. In Section II, we present our system model. Section III gives a detailed description of the proposed scheme. In section IV, the proposed scheme is evaluated through simulation. The paper is concluded in Section V.

II. System Model

We consider a CRN that consists of N_c SUs, where every SU is equipped with M_T antennas and an FC, which works as a common receiver.

In order to protect LUs from the interference, spectrum sensing is performed by each SU. In this paper, we utilize an energy detection technique for the existence of the LUs in the network. Among various techniques, the energy detection is a reliable technique when no prior information of the LUs is available. Each SU performs local sensing by utilizing the energy detection and the sensing information is transmitted to the FC, that makes a global decision on the existence of the LU in the network.

The local sensing performed by an SU (with a single energy detector/antenna) at time slot n can be formulated as binary hypotheses such as

$$y_i(\mathrm{n}) = \begin{cases} z(n) & ;H_0, \\ h_i(n)s(n)+z(n) & ;H_1, \end{cases} \tag{1}$$

where H_0 is the hypotheses of LU's absence, H_1 is the hypotheses of LU's presence, $h_i(n)$ is the fading coefficient, $z(n)$ is the additive white Gaussian noise (AWGN), $s(n)$ is the transmitted signal of the LU, and $y_i(\mathrm{n})$ is the signal received at the *i-th* SU, respectively.

Energy of the received signal can be determined by

$$X_{Ei}(\mathrm{n}) = \sum_{k=1}^{N_T} \left| y_k(n) \right|^2 \tag{2}$$

where $N_T = 2TW$, T is the sensing time, W is the bandwidth, and y_k is the j-th sample of the received signal. If N_T is large enough, X_{Ei} can be well approximated as a Gaussian distribution by central limit theorem (CLT) [18].

III. Proposed Scheme

In this section, we present the proposed multi-antenna technique with multi-band based on D-S theory and proposed the reporting mechanism in detail.

A. Multi Antenna Technique with Multi-Band Spectrum Sensing Based on D-S Theory

The CSS mainly consists of three steps: (1) local sensing performed by each SU, (2) reporting the sensing information to the FC, and (3) final processing for a global decision at the FC. In our proposed scheme, in the local sensing stage; sensing is performed by multiple antennas with multiple sub-bands instead of a single band. In the reporting stage, the information for multiple sub-bands is sent in an ordered sequential manner to the FC by the proposed reporting mechanism. At the final stage, upon receiving the targeted detection and false alarm probabilities, the FC manages to stop reporting for all SUs. The D-S evidence theory is utilized to declare the presence or absence of LU in the network.

We consider a CRN with bandwidth W which is divided into total B dis-joint narrow sub-bands, and is given by

$$W = \bigcup_{b=1}^{B} W^b \quad , \ \mathrm{W}^{\mathrm{b}} = \left[w_b, w_{b+1} \right), \tag{3}$$

The received signal consists of total B sub-bands with the boundaries located at $w_1 < \mathrm{w}_2 < \ldots < \mathrm{w}_{\mathrm{B+1}}$.

The signal received at any antenna consists of two components: the transmitted signal multiplied by the channel co-efficient and the other is additive white Gaussian noise (AWGN). The signal received from the multiple antennas goes through the energy detector, and the local sensing is performed at every SU.

The received sample at the *b-th* band can be binary hypotheses as

$$y^b{}_{i,\mathrm{j}}(\mathrm{n}) = \begin{cases} z_{i,\mathrm{j}}(n) & ;H_0 \\ h^b{}_{i,\mathrm{j}}(n)s(n)+z_{i,\mathrm{j}}(n) & ;H_1 \end{cases}, \tag{4}$$

where $y^b{}_{i,\mathrm{j}}(\mathrm{n})$ is the received signal from the *i-th* SU at the *j-th* antenna in the *b-th* sub-band, $i = 1,2,\ldots \mathrm{N_c}$, $j = 1,2,\ldots \mathrm{M_T}$, $b = 1,2,\ldots \mathrm{B}$, and $n = 1,2,\ldots \mathrm{N_T}$. N is the number of SUs, M is the number of antennas, B is the number of sub-bands, and N_T is the number of samples per each band.

Since we assume that multiple antennas are un-correlated, SUs are independent and share the same spectrum with the LU. The signal received from each antenna is multiplied by a weighting factor ω. Energy at each antenna is calculated independently and the energy is added for signal detection. For the multiple bands operation, it is required to minimize the processing complexity. Hence, we utilize an equal gain combining (EGC) given by

$$X^b{}_{Ei,j}(n) = \sum_{j=1}^{N_T} \omega_{i,j} \left| y^b{}_{i,j}(n) \right|^2 , \tag{5}$$

The signal from the multiple antennas can be combined at each SU by using the EGC method, which can be written as

$$E = \sum_{j=1}^{M_T} X^b{}_{Ei,j}(\mathrm{n}). \tag{6}$$

According to *CLT*, E can be well-approximated as a Gaussian random variable under both hypotheses H_0 and H_1 [18].

In this paper, we utilize the D-S evidence theory for final decision about the existence of the LU. According to the D-S evidence theory, the frame of discernment *{Ar}* can be defined as $\{H_0, H_1, \Omega\}$, where Ω is the ignorance hypotheses which denotes whether the hypotheses is true or not. Each SU estimates its self-assessed credibility, which is equivalent to basic probability assignment (BPA) for hypotheses H_0 and H_1. The BPA function is defined as a cumulative distribution function as follows [10].

$$\begin{cases} H_0: \; m^b{}_i\left(H_0\right) = \displaystyle\int_{E_i}^{\infty} \frac{1}{2\pi\sigma_{0i}} e^{-\frac{\left(X^b{}_{E_i} - \mu_{0i}\right)^2}{\sigma_{0i}^2}} \, \mathrm{dx}, \\ \\ H_1: \; m^b{}_i\left(H_1\right) = \displaystyle\int_{E_i}^{\infty} \frac{1}{2\pi\sigma_{1i}} e^{-\frac{\left(X^b{}_{E_i} - \mu_{1i}\right)^2}{\sigma_{1i}^2}} \, \mathrm{dx}, \end{cases} \tag{7}$$

where $m^b{}_i\left(H_0\right)$ and $m^b{}_i\left(H_1\right)$ are the BPA hypotheses of the *i-th* SU, respectively.

Once the BPA of the *i-th* SU is determined, the average reliability of the SU with B bands is defined as

$$\mathrm{r}_{avgi} = \frac{\sum_{b=1}^{B} \log\left|\dfrac{m^b{}_i\left(H_1\right)}{m^b{}_i\left(H_0\right)}\right|}{B}. \tag{8}$$

The main problem of the evidence-based data fusion is that a large number of communication resources are required for reporting the sensing results. In order to reduce the overhead, we propose a sequential CSS. In this scheme, each SU transmits its assessed BPA information to FC according to their credibility. The BPA at the FC is sequentially combined in order of the data arrived as

$$m^b{}_{k,global}\left(H_j\right) = m^b{}_{k-1,global}\left(H_j\right) \oplus m^b{}_{k,global}\left(H_j\right), \tag{9}$$

where $\mathrm{j} \in [0,1]$, and $m^b{}_{k,global}\left(H_j\right)$, and $m^b{}_{k-1,global}\left(H_j\right)$ are the *k-th* and the *(k-1)-th* global BPA hypotheses H_j, respectively and $\oplus$ denotes the combination operator.

The global decision at the DFC is based on the global combination ratio of the k-reports and is given by

$$\mathrm{r}^b{}_{k,global} = \left(\frac{m^b{}_{k,global}\left(H_1\right)}{m^b{}_{k,global}\left(H_0\right)}\right), \tag{10}$$

The following two strategies are applied at FC for global decision. When the number of reports, *k*, at the FC is less than the total number of SUs, the global decision at the b-th band can be determined as

$$F_d{}^b = \begin{cases} H_0: & \mathrm{r}^b{}_{k,global} < -\eta, \\ H_1: & \mathrm{r}^b{}_{k,global} > \eta, \\ \textit{no decision}: & -\eta < \mathrm{r}^b{}_{k,global} < \eta, \end{cases} \tag{11}$$

where $-\eta < \mathrm{r}^b{}_{k,global} < \eta$ implies that the reports at the FC are not enough to make a global decision and wait for the next data report. When the number of reports *k* is equal to the total number of SUs at the FC, the global decision for the *b-th* band can be determined as

$$F_d{}^b = \begin{cases} H_0: & \mathrm{r}^b{}_{k,global} < 0 \\ H_1: & \mathrm{r}^b{}_{k,global} > 0 \end{cases}. \tag{12}$$

B. Proposed Reporting Mechanism

In the propose reporting mechanism, the total reporting period consists of two parts: reservation period and reporting period as shown in Fig.1.

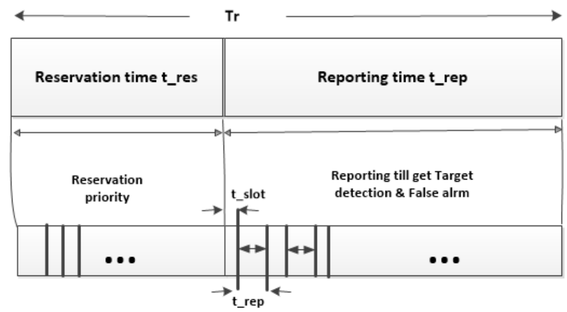

Fig. 1. Propose reporting model.

The SU with a higher sensing reliability will have an earlier order in the reservation time and report its priority basis to the FC in the reporting period. Before transmitting the sensing report, all SUs listen for a short time duration for the burst signal from the FC, which is equivalent to the time slot. Whenever a final decision is made, the FC generates a burst signal to stop reporting and distribute the final decision message to all SUs.

The total sensing time duration varies according to the number of antennas and bands. The sensing time duration for a single band requires only a certain number of samples for the band and does not need additional time expense for sensing. The sensing time duration for a single band and a single antenna is given by

$$T_{ss} = N_s t_e, \tag{13}$$

where N_s is the number of samples and t_e is the time consumed for single bit sensing.

Once the sensing is performed, all the bands of SUs are reported in a single time slot. In the first phase, all SUs perform reservations in a sequential reporting manner, and in the second phase the SUs with higher priority reports to the FC.

In case of single-band and single-antenna, the total reporting time duration is given by

$$T_r = N_{C1}\left(t_{rep} + t_{slot}\right) + t_{res}, \tag{14}$$

where t_{res} is the reservation time duration, N_{C1} is the required number of SUs to obtain target probability of detection and false alarm, t_{rep} is the reporting time duration, and t_{slot} is the slot time duration, respectively.

The sensing performed by multiple antennas is performed in parallel and no additional time is required. A very small amount of extra time is required for combining energies. Thus, in case of sensing time for single-band and multi-antenna is given by

$$T_{sm} = N_s t_e + \mathrm{t}_{\mathrm{comb}}, \tag{15}$$

where $\mathrm{t}_{\mathrm{comb}}$ is the required time duration combining additional energies from multiple antennas. The total reporting time for single-band and multi-antenna is given by

$$T_r = N_{C2}\left(t_{rep} + t_{slot}\right) + t_{res}, \tag{16}$$

where N_{C2} is the number of SUs to obtain the targeted probabilities of detection and false alarm for multiple antennas. In case of multiple bands, when each band is sensed individually, it requires B time duration for single-antenna with B bands and can be computed by

$$T_{ms} = \sum_{b=1}^{B} N_s t_e. \tag{17}$$

For single-antenna and multi-band, the reservation time is identical. However, the slot time depends on the number of reports. Since every SU sends data in multiple bands, the reporting time increases. In case of multi-band and single-antenna, the total reporting time is given by

$$T_r = N_{C1}\left(\bar{t}_{rep} + t_{slot}\right) + t_{res}, \tag{18}$$

where $\bar{t}_{rep}$ is the reporting time for multi-band and $\bar{t}_{rep} > t_{rep}$.

In case of multi-band and multi-antenna the sensing time is given by

$$T_{mm} = \sum_{b=1}^{B} N_s t_e + \mathrm{t}_{\mathrm{comb}}. \tag{19}$$

The total reporting time for multi-band with multiple antennas is given by

$$T_r = N_{C2}\left(\bar{t}_{rep} + t_{slot}\right) + t_{res}, \tag{20}$$

IV. Numerical Results

The numerical results are evaluated under a variety of different conditions. For simulation results, we consider 100 SU nodes which independently sense the existence of LUs in the network. We assume that the LU activity is 0.5 and the bandwidth per sub-band is *6 MHz*.

Fig. 2 shows the global probabilities of detection and false alarm for varying SNRs (-14 to -10 dB). The performance shown in Fig.2 is for 10% reporting of total nodes. The comparative performance is shown by a single antenna and four antennas (i.e., M =1 and M=4), where every SU performs sensing on a single band and multiple bands (i.e., B=1 and B=4). From Fig. 2, it is evident that the global detection probability is higher and false alarm probability is lower, when we consider multiple antennas, compared with single-antenna and vice versa. Moreover, for multiple bands, the probability of false alarm increases and the probability of detection decreases due to the decrement of reliability for multiple bands.

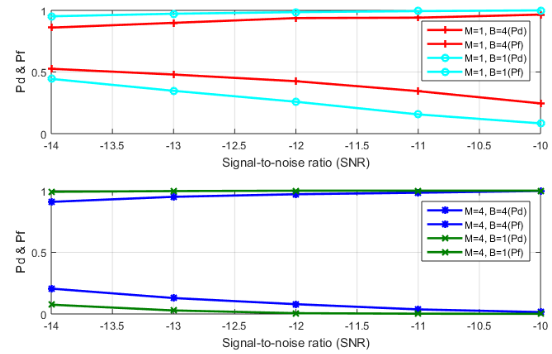

Fig. 2. ROC curve for a single and multiple antennas with multiple bands.

The total error probability for different percentage of reporting is presented in Fig. 3. It is assumed that every SU endures -14 dB SNR. The total error probability is defined as a combination of the probabilities of miss detection and false alarm and for B bands, it can be written as follows:

$$error = \frac{\sum_{b=1}^{B} P_f^{\,b} P(H_0) + \left(1 - P_d^{\,b}\right) P(H_1)}{B}.$$

From Fig.3, it can be observed that the total error probability decreases as the number of reports increases. In addition, multiple bands give higher probability of error, compared with single-band. Moreover, utilizing four antennas provides a lower error probability compared with utilizing a single antenna.

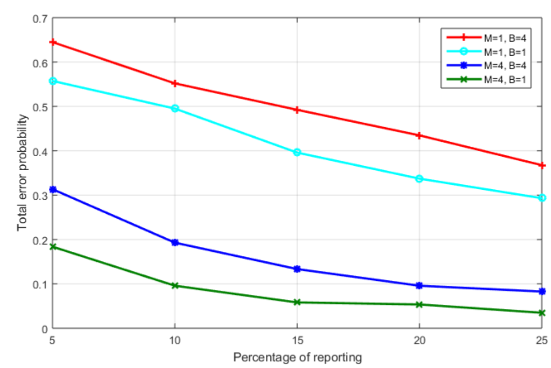

Fig. 3 Total error probability vs. percentage of reporting.

Fig. 4 shows the required reporting time to obtain target probabilities of detection and false alarm for varying SNR. It is depicted in Fig.4, that the multi-band and single-antenna (i.e., B=4, M=1) case give the highest reporting time. For single-band with single-antenna has the second highest reporting time but the SU with multiple antennas has significantly lower reporting time, compared with SU with a single antenna. The reporting time duration is approximately more than 3 to 4 times higher than the multi-antenna case.

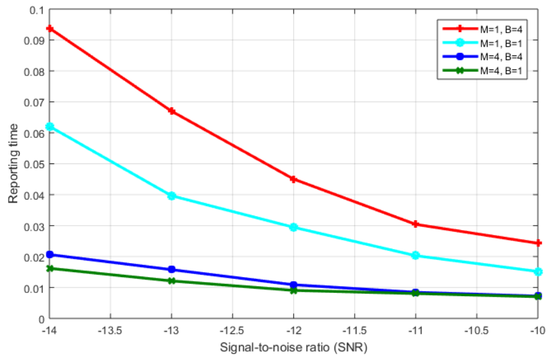

Fig. 4. Reporting time vs SNR to obtain target probabilities of detection and false alarm.

V. CONCLUSION

In this paper, we proposed a multi-antenna multi-bands based cooperative spectrum sensing scheme. Also, a reporting mechanism for the multi-band and multi-antenna case is analyzed. It is well justified that the ordered sequential reporting based on D-S evidence theory can efficiently reduce the reporting time and the total error probability. The performance of the proposed scheme is evaluated in term of probability of detection, probability of false alarm, total probability error, and reporting time for different values of the number of antennas and sub-bands.

For future work, we will consider the throughput performance analysis of the multi-antenna multi-band cooperative spectrum sensing scheme.

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