Energy-Efficient Channel Management Scheme for Cognitive Radio Sensor Networks

Jeong Ae Han, Wha Sook Jeon, *Senior Member, IEEE*, and Dong Geun Jeong, *Senior Member, IEEE*

***Abstract*—In designing a cognitive radio sensor network (CRSN), we need to take account of energy both efficiency and primary user (PU) protection since the CRSN consumes additional energy to support CR functionality such as channel sensing and switching, which can shorten the network lifetime. In this paper, we propose a new channel management scheme for CRSNs, which heightens the energy efficiency while not greatly disturbing a PU. The CRSN with the proposed scheme adaptively selects its operation mode among channel sensing, channel switching, and data transmission/reception, according to the channel-sensing outcome. Considering that the sensing outcome can be erroneous due to noise uncertainty, we design the proposed scheme on the basis of the partially observable Markov decision process framework. The simulation results show that the proposed scheme energy-efficiently operates while properly protecting a PU.**

***Index Terms*—Channel management, cognitive radio sensor networks (CRSNs), energy efficiency, partially observable Markov decision process (POMDP).**

I. Introduction

Low-cost, low-data-rate, and low-power wireless sensor networks have been used in many applications, including home automation, personal health care, surveillance, etc. [1]. Most wireless sensor networks utilize the license-exempt industrial, scientific, and medical (ISM) band. However, as discussed in [2], the ISM band is very crowded since many other communication systems are already operating on the band. As a solution to overcome the lack of available radio spectrum for wireless sensor networks, the cognitive radio (CR) technology can be considered [3]. A CR sensor network (CRSN) exploits channels that are licensed to primary users (PUs) but are not used by them at a specific time and in a specific area.

Since PUs have the privilege of using the channels, a CRSN should not disturb the transmission of PU. To this end, a CRSN continually senses its operating channel for detecting PU activity. If the CRSN detects PU appearance on the channel, it changes the operating channel to another vacant channel (the channel that is not used by PU) as soon as possible. To accomplish fast channel switching by reducing the time needed for searching another vacant channel (i.e., a new operating channel), the CRSN may prepare a candidate for the new operating channel in advance. This candidate channel is called the backup channel.

Manuscript received June 19, 2010; revised November 19, 2010 and January 17, 2011; accepted March 1, 2011. Date of publication March 14, 2011; date of current version May 16, 2011. The work of W. S. Jeon was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (2010-0027692). The work of D. G. Jeong was supported by the Hankuk University of Foreign Studies Research Fund. The review of this paper was coordinated by Dr. T. Taleb.

J. A. Han, and W. S. Jeon are with the School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea (e-mail: han@wn.snu.ac.kr; wsjeon@snu.ac.kr).

D. G. Jeong is with the Department of Electronics Engineering, Hankuk University of Foreign Studies, Yongin 449-791, Korea (e-mail: dgjeong@hufs.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2011.2128355

If a PU appears on the operating channel, the data transmission/reception in CRSN is suspended during the channel switching. This intermittent disruption of data transmission can degrade the quality of service (QoS) of real-time traffic. Reference [4] has proposed a CRSN that can guarantee the QoSs of both real-time traffic and best-effort traffic, and [5] has suggested two resource allocation policies for supporting real-time constant-bit rate traffic in CRSN.

On the other hand, as discussed above, a CRSN should perform not only conventional sensor network operations such as data transmission/reception but also CR-inherent operations, such as channel sensing and channel switching. These additional CR-inherent operations for channel management make CRSNs consume more energy than conventional sensor networks. Now, we are facing two conflicting requirements in designing CRSNs, i.e., a frequent and long channel sensing for improving PU protection performance and an infrequent and short channel sensing for saving the energy of sensor nodes.

Several schemes for improving energy efficiency in CRSNs have been proposed in the literature. In [6]–[8], new sensing schemes for saving energy in CRSNs have been suggested. Among these, [6] has proposed an energy-saving sensing architecture for multiresolution spectrum sensing, and the scheme in [7] clusters the sensor nodes to reduce the energy consumption during the sensing-result reporting. The channel-sensing scheme proposed in [8] saves energy by choosing the optimal sleep period and censoring parameters. On the other hand, the scheme in [9] decreases the energy consumption by controlling the power and rate for data transmission on the already acquired vacant channels. Note that all these schemes focus on energy efficiency in a specific operation (e.g., channel sensing or data transmission). However, the overall CRSN operation consists of several modes of operation: data transmission/reception, operating channel sensing, backup channel sensing, change of operating channel, and replacement of backup channel. Thus, the energy efficiency can be improved more when all modes of operations are taken into account together in designing CRSNs.

In this paper, we propose an operation mode selection scheme for improving energy efficiency in CRSNs, which is a kind of channel-management scheme. We consider a sensor node being equipped with one transceiver for low cost. Then, the CRSN can perform only one mode of operation at a time, and the overall operation of the CRSN can be modeled as a series of decision making on the operation mode. The proposed scheme adaptively selects an operation mode, depending not only on the sensing outcomes of the operating channel and the backup channel but also on the energy consumption of each operation mode. Considering that the sensing outcomes can be erroneous due to the random noise, we design the operation mode selection scheme for CRSNs on the basis of the partially observable Markov decision process (POMDP) framework, which is well known as a very appropriate framework for modeling a decision-making problem with uncertainty [10].

The remainder of this paper is organized as follows: Section II describes the system model under consideration, and Section III presents the proposed scheme based on POMDP. We discuss the performance of the proposed scheme with some simulation results in Section IV and conclude this paper in Section V.

II. System Model

A. *CRSN Model*

We consider a small-scale CR sensor network with star topology, which is composed of one cluster head (CH) and $(N-1)$ cluster members. In the CRSN under consideration, the CH functions as a

0018-9545/$26.00 © 2011 IEEE

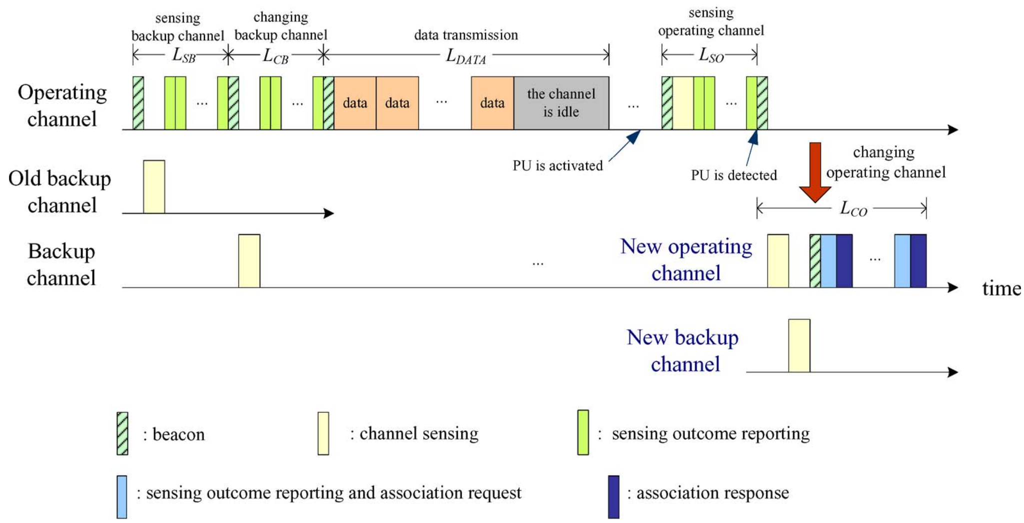

Fig. 1. Example of operation in a CRSN.

central controller of the network, and the cluster members communicate only with the CH, under the control of the CH. There are M channels, each of which has the same bandwidth B. All channels have the same PU activation model, where a channel alternates the PU active state and the PU inactive state. The active (inactive) duration of PU on the channel is exponentially distributed with the average $1/\lambda$ $(1/\mu)$. Thus, the probability P_e that a randomly selected channel is vacant is $\mu/(\lambda+\mu)$.

The CRSN operates on a channel where a PU is not detected, which is called the operating channel. It also manages another channel where a PU is not detected, as the backup channel. The CRSN has five operation modes, which are data transmission/reception $(DATA)$, sensing the operating channel (SO), sensing the backup channel (SB), changing the operating channel (CO), and changing the backup channel (CB). The lengths of these operation modes are denoted by $L_{\rm DATA}$, $L_{\rm SO}$, $L_{\rm SB}$, $L_{\rm CO}$, and $L_{\rm CB}$, respectively.

The channel time is divided into frames, each of which starts with a beacon. At the beginning of each frame (which is the decision epoch), the CH selects one operation mode among five modes and informs the cluster members of the selected mode via a beacon. Since the selected mode is effective for the corresponding frame, the frame length is equal to the length of the selected mode. Thus, the frame length is variable, depending on the selected mode. The system operation at each mode will be described in Section III-A in more detail.

B. Channel Sensing

We consider the simple energy detection [11] technique as a physical sensing method since the sensor node requires low-cost implementation. When the CH selects SO or SB as the operation mode, it broadcasts the sensing start time and sensing duration through the beacon. Then, all sensor nodes, including the CH, measure the received energy on the target (operating or backup) channel for the given sensing duration, and the cluster members report their sensing outcomes (i.e., the received energy) to the CH. Note that these sensing outcomes should be transmitted within the frame where the sensing is carried out since they are used for deciding the operation mode of the next frame. For this, the CH makes a reporting schedule immediately after sensing within the same frame.

The CH takes the sum of the received energies reported from all sensor nodes including itself divided by the noise spectral density, as a test statistic. Let $s_t^{(m)}$ be the test statistic for channel m, which is measured for the sensing duration T_s at the $(t-1)$th frame. According to [11], under the hypothesis H_0 that channel m is vacant, the probability density function (pdf) of $s_t^{(m)}$ is the chi-square distribution with $2BT_sN$ degrees of freedom. Under the hypothesis H_1 that a PU exists on channel m, $s_t^{(m)}$ follows the noncentral chi-square distribution with $2BT_sN$ degrees of freedom and the noncentral parameter E/N_0, where E is the sum of the PU signal energies received by the sensor nodes, and N_0 is the noise spectral density.

To more easily treat the continuous random variable $s_t^{(m)}$ in the POMDP framework, we quantize the value of $s_t^{(m)}$ into K levels. For this, we introduce $(K+1)$ thresholds, $\gamma_0,\ldots,\gamma_K$, where $\gamma_0<\gamma_1<\cdots<\gamma_K$, $\gamma_0=-\infty$, and $\gamma_K=+\infty$. Let $o_t^{(m)}$ denote the quantized value of $s_t^{(m)}$. For $k=1,2,\ldots,K$, if $\gamma_{k-1}<s_t^{(m)}\le\gamma_k$, $o_t^{(m)}=k$. That is, the quantized test statistic $o_t^{(m)}$ is calculated using $s_t^{(m)}$, which is the sum of sensing results divided by the noise spectral density. We define the conditional probabilities $v_0(k)\triangleq Pr\{o_t^{(m)}=k|H_0\}=Pr\{\gamma_{k-1}<s_t^{(m)}\le\gamma_k|H_0\}$, $\forall m$, and $v_1(k)\triangleq Pr\{o_t^{(m)}=k|H_1\}=Pr\{\gamma_{k-1}<s_t^{(m)}\le\gamma_k|H_1\}$, $\forall m$. Then, $v_0(k)$ and $v_1(k)$ can be easily calculated with the pdfs of $s_t^{(m)}$.

III. Proposed Operation Mode Decision Scheme

A. Operation Mode

At each decision epoch, the CH selects one of five operation modes (i.e., $DATA$, SO, SB, CO, and CB) and notifies its cluster members of the selected mode via a beacon. Fig. 1 shows an example of the CRSN operations over time. The work that the sensor nodes perform in each operation mode is given as follows:

In the SO (SB) mode, the CH instructs all cluster members, including the CH, to sense the operating (backup) channel, and each cluster member reports its sensing outcomes to the CH.[1] Then, the CH determines the next operation mode, based on the state of the operating (backup) channel estimated with the reported sensing outcomes. On the other hand, in the CB mode, the CH randomly chooses one channel as the new backup channel and orders the cluster members to sense the chosen channel. Like in the SB or SO mode, the CH

[1]The CH schedules all packet transmissions within the CRSN, according to a time-division fashion. Then, each cluster member that receives the transmission scheduling information via a beacon reports the sensing result during the time exclusively allocated to itself.

estimates the state of the new backup channel with the reported sensing outcomes and selects the next operation mode, depending on this estimated channel state.

During the $DATA$ mode, the CH broadcasts the transmission scheduling information to the cluster members through the beacon, and each cluster member transmits the data to the CH according to the transmission schedule and goes to sleep immediately after its data transmission. When receiving data from all cluster members, the CH also sleeps. At the end of the $DATA$ mode, the CH wakes up and determines the next operation mode. During the CO mode, all sensor nodes, including the CH, sense both the new operating channel, which was the backup channel, and the new backup channel, which is randomly selected by CH. When the CRSN operates on the new channel, all cluster members need to be newly associated with the CH. That is, the CH transmits an additional beacon for synchronization on the new operating channel, and each cluster member sends an association message to notify that it has successfully joined, as well as the sensing results of both channels. Then, the CH confirms the reception of each association message by sending an association response message. After collecting the sensing outcomes from all sensor nodes, the CH determines the next operation mode based on these sensing outcomes. It is noted that if the next mode is not the CO mode, the CRSN operates on this new channel.

B. POMDP Framework

We adopt a POMDP framework, which permits the uncertainty of information in modeling the operation mode selection problem. This is because the states of the operating and backup channels cannot be known exactly to the CRSN, and the CRSN merely can guess whether a PU exists on the operating or backup channel, based on the sensing results. Under the POMDP model, the CRSN always selects the operation mode from which it can obtain the highest reward for these estimated channel states. The detailed description of the POMDP model for the proposed scheme is given as follows:

1) Core Process $\{X_t\}$: The state of core process X_t represents the states of operating and backup channels at the decision epoch t. For convenience in description, we regard the operating channel and the backup channel as channel 1 and channel 2, respectively. Thus, $X_t = (x_t^{(1)}, x_t^{(2)})$, where $x_t^{(m)} = 0$ means that channel m is vacant, and $x_t^{(m)} = 1$ indicates that a PU exists on channel m.

2) Action A_t: Action A_t represents an operation mode chosen by the CH at decision epoch t, and $\mathcal{A}$ denotes the set of feasible operation modes. That is, $\mathcal{A} = \{DATA, SO, SB, CO, CB\}$, and $A_t \in \mathcal{A}$.

3) Transition Probability of Core Process $\mathcal{P}$: When action a is taken, the transition probability matrix of the core process is $\mathcal{P}(a) = [p_{(i,j)(i',j')}(a)]$, where $p_{(i,j)(i',j')}(a) = Pr\{X_{t+1} = (i',j')|X_t = (i,j), A_t = a\}$. Transition probability $p_{(i,j)(i',j')}(a)$ can be calculated using the following two probabilities: When action a is taken, $u_{i,i'}(a)$ is the probability that a channel transits from state i to i', and $w_i(a)$ denotes the probability that the channel selected randomly at a decision epoch is in state i immediately before the next decision epoch. Note that L_a denotes the time duration of action a. For example, when action CO is selected, $L_a = L_{\mathrm{CO}}$. Then, $u_{0,0}(a) = e^{-\lambda L_a}$, $u_{0,1}(a) = 1 - e^{-\lambda L_a}$, $u_{1,0}(a) = 1 - e^{-\mu L_a}$, and $u_{1,1}(a) = e^{-\mu L_a}$. In addition, $w_0(a) = P_e e^{-\lambda L_a} + (1 - P_e)(1 - e^{-\mu L_a})$, and $w_1(a) = (1 - P_e)e^{-\mu L_a} + P_e(1 - e^{-\lambda L_a})$, where P_e is the probability that a randomly selected channel is vacant, as mentioned in Section II-A.

For $a \in \{DATA, SO, SB\}$, $p_{(i,j)(i',j')}(a) = u_{i,i'}(a) \times u_{j,j'}(a)$. If the CH selects action CO in state (i,j), the state of the operating channel is j immediately after selection since the backup channel becomes a new operating channel. Therefore, the probability that the new operating channel is in state i' at the end of the CO mode (i.e., the next epoch) is $u_{(j,i')}(CO)$. On the other hand, when selecting action CO, the CH randomly selects one channel as a new backup channel. Thus, the probability that the state of this new backup channel is j' at the end of the CO mode is $w_{j'}(CO)$. Since the states of the operating channel and the backup channel are independent of each other, $p_{(i,j)(i',j')}(CO) = u_{(j,i')}(CO) \times w_{j'}(CO)$. Similarly, $p_{(i,j)(i',j')}(CB) = u_{i,i'}(CB) \times w_{j'}(CB)$ since a new backup channel will be randomly selected while the operating channel is not changed under action CB.

4) Observation Process $\{O_t\}$: The state of the observation process at decision epoch t is denoted by $O_t = (o_t^{(1)}, o_t^{(2)})$, where $o_t^{(m)}$ $(m = 1, 2)$ represents the quantized test statistic obtained by sensing channel m during the $(t-1)$th frame, and $o_t^{(m)} \in \{1, 2, \ldots, K\}$. When the CRSN does not sense channel m and has no test statistic for channel m, $o_t^{(m)}$ is set to 0. Thus, $o_t^{(1)} = 0$ for $A_{t-1} \in \{DATA, SB, CB\}$, and $o_t^{(2)} = 0$ for $A_{t-1} \in \{DATA, SO\}$.

5) Relation Between Core and Observation Processes $\mathcal{Q}$: Let $\mathcal{Q}(a) = [q_{(i,j)(k,l)}(a)]$ denote the probabilistic relation between the core process state and the observation process state. That is, $q_{(i,j)(k,l)}(a) = Pr\{O_t = (k,l)|X_t = (i,j), A_{t-1} = a\}$. When $n(k)$ denotes the probability of $o_t^{(m)} = k$ for channel m not to be sensed, $n(0) = 1$, and $n(k) = 0$ for all $k \geq 1$, regardless of channel state $x_t^{(m)}$. Then, $q_{(i,j)(k,l)}(a)$ can be defined with $v_i(k)$ (defined in Section II-B) and $n(k)$. Since the CRSN under action $DATA$ senses no channel, $q_{(i,j)(k,l)}(DATA) = n(k) \times n(l)$. Considering that only the operating channel is sensed under action SO, $q_{(i,j)(k,l)}(SO) = v_i(k) \times n(l)$. Also, under action CB or SB, where only the backup channel is sensed, $q_{(i,j)(k,l)}(CB) = n(k) \times v_j(l)$, and $q_{(i,j)(k,l)}(SB) = n(k) \times v_j(l)$. Furthermore, $q_{(i,j)(k,l)}(CO) = v_i(k) \times v_j(l)$ since the CRSN senses both channels under action CO.

6) Reward R: Let $r_{(i,j)(i',j')}(a)$ be the immediate reward that the CRSN receives by taking action a in state (i,j), which results in a transition to (i',j'). Then, the total expected reward obtained by performing action a at state (i,j) is

$$R_{(i,j)}(a) = \sum_{i'=0}^{1} \sum_{j'=0}^{1} r_{(i,j)(i',j')}(a) p_{(i,j),(i',j')}(a). \tag{1}$$

The immediate rewards are the control parameters for getting the required performance. Thus, the rewards should be determined to reduce the energy consumption while suitably protecting PUs. In simulation, we will set the values of these rewards, in consideration of the consumed energy and the possibility for PU disturbance.

C. Proposed Optimal Operation Decision Scheme Based on POMDP

For the operation mode selection, the CRSN manages information vector $\Pi(t)$, which summarizes all of the information required for the decision making at decision epoch t [10]. Information vector $\Pi(t)$ is represented by $(\pi_{(0,0)}(t), \pi_{(0,1)}(t), \pi_{(1,0)}(t), \pi_{(1,1)}(t))$, where $\pi_{(i,j)}(t)$ is the probability that core process X_t is in state (i,j). At the network initialization, since the CRSN does not have any information about channel state, the initial information vector $\Pi(0)$ is assumed to be the stationary channel state probability vector. Thus, $\Pi(0) = \{\mu^2/(\lambda+\mu)^2, \mu\lambda/(\lambda+\mu)^2, \lambda\mu/(\lambda+\mu)^2, \lambda^2/(\lambda+\mu)^2\}$.

According to the property of POMDP [10], we can infer information vector $\Pi(t+1)$, from action A_t, information vector $\Pi(t)$, and observation O_{t+1}. The transformation of $\Pi(t)$ to $\Pi(t+1)$ can be specified by Bayes' formula, as in (2), shown at the bottom of the page. At decision epoch $(t+1)$, the CH calculates $\Pi(t+1)$ by using (2).

To select the action with the updated information vector, the CH relies on a policy δ, which is a mapping function from the information vector to an action. There can be many feasible policies. Among all possible policies, we need to find the optimal policy δ^*, which maximizes the expected discounted infinite horizon reward with the discount factor β $(0 \leq \beta < 1)$.

For finding the optimal policy $\delta^*(\Pi)$, we define the optimal value function $V^*(\Pi)$ as in (3), shown at the bottom of the page, where $Pr\{(k,l)|\Pi, a\} = \sum_{i'=0}^{1}\sum_{j'=0}^{1}(q_{(i',j')(k,l)}(a) \times \sum_{i=0}^{1}\sum_{j=0}^{1}\pi_{(i,j)}p_{(i,j)(i',j')}(a))$. Then, the optimal policy $\delta^*(\Pi)$ is derived by using $V^*(\Pi)$, as in (4), shown at the bottom of the page. The optimal value function $V^*(\Pi)$ and the optimal policy $\delta^*(\Pi)$ can be computed by the value iteration based on dynamic programming. Furthermore, the optimal policy can be derived offline in advance before starting the CRSN.

D. Implementation of the Proposed Scheme

1) Mode Selection: The optimal policy δ^*, which is composed of all feasible information vectors and their respective optimal actions, is stored in the CH. The detailed mode selection procedure of the proposed scheme is given as follows:

a) At the beginning of frame t (the decision epoch t), the CH selects the optimal operation mode $A_t = a^*$ with information vector $\Pi(t)$.
b) The CH informs the nodes of the selected operation mode A_t through a beacon.
c) After receiving a beacon, all sensor nodes perform the selected A_t (see Section III-A for the work of the nodes under each operation mode).
d) The CH calculates the quantized test statistic O_{t+1} using the sensing results reported from the nodes (O_{t+1} is set to 0 for the channel where no sensing result is obtained). On the basis of A_t and O_{t+1}, the CH updates information vector $\Pi(t)$ to $\Pi(t+1)$ by using (2).

The proposed CRSN repeats the preceding work every frame.

2) Policy Update: It is noted that the optimal policy is computed with an assumption that the CRSN already knows the total sum of the received PU powers at the nodes and the PU activity pattern. When these values used for obtaining the policy are largely different from the actual measured values, the policy should be updated. For this, the CRSN estimates the expected sum of the received PU powers from the history of the measured PU power and may try to periodically update its policy by recomputing the policy with this estimated power.[2] As time goes on, the CRSN can have a more proper policy for its environment.

IV. Performance Evaluation

A. Simulation Setting

We refer to the IEEE 802.15.4 system in setting the values of simulation parameters. The bandwidth B of a channel is set to 2 MHz, and the transmission rate of CRSN is fixed to 250 kb/s. As shown in Fig. 1, various types of packets are defined in the proposed scheme. In simulation, the sizes of a beacon, a sensing outcome reporting packet, a sensing outcome reporting/association request packet, and an association response packet are set to 40, 22, 31, and 27 bytes, respectively, and the size of data packet carrying data of 100 bytes is 113 bytes. All packet transmissions within the CRSN are scheduled by the CH according to a time-division fashion, and as a result, each cluster member can send the data or control packets to the CH, without contention with other nodes. In addition, all packet transmissions are separated by a short interframe spacing of 192 μs. With these parameter values, the lengths of operation modes are $L_{\mathrm{SO}} = L_{\mathrm{SB}} = L_{\mathrm{CB}} = 9.5$ ms and $L_{\mathrm{CO}} = 22.4$ ms. The length of $DATA$ mode is $L_{\mathrm{DATA}} = 50$ ms, where the active duration is set to 31 ms, so that the maximum data rate of sensor application can be 16 kb/s. In any operation mode, a sensor node sleeps when it does not transmit

[2]The computation of policy may be done by the CH within the CRSN or the outside central system like a data center. When the data center calculates the policy, the CRSN regularly reports the measured PU power to the data center. Then, the data center computes more accurate policy, reflecting the real results, and sends it to the CH.

$$\begin{aligned}\pi_{(i,j)}(t+1) &\equiv T_{(i,j)}\left(\Pi(t), a, (k,l)\right)\\ &= Pr\left\{X_{t+1} = (i,j)|\Pi(t), A_t = a, O_{t+1} = (k,l)\right\}\\ &= \frac{q_{(i,j)(k,l)}(a)\sum_{i'=0}^{1}\sum_{j'=0}^{1}p_{(i',j')(i,j)}(a)\pi_{(i',j')}(t)}{\sum_{\tilde{i}=0}^{1}\sum_{\tilde{j}=0}^{1}q_{(\tilde{i},\tilde{j})(k,l)}(a)\sum_{i'=0}^{1}\sum_{j'=0}^{1}p_{(i',j')(\tilde{i},\tilde{j})}(a)\pi_{(i',j')}(t)}\end{aligned} \tag{2}$$

$$V^*(\Pi) = \max_{a\in\mathcal{A}}\left\{\sum_{i=0}^{1}\sum_{j=0}^{1}\pi_{(i,j)}R_{(i,j)}(a) + \beta\sum_{k=0}^{K}\sum_{l=0}^{K}V^*\left(T\left(\Pi, a, (k,l)\right)\right)\times Pr\left\{(k,l)|\Pi, a\right\}\right\} \tag{3}$$

$$\delta^*(\Pi) = \arg\max_{a\in\mathcal{A}}\left\{\sum_{i=0}^{1}\sum_{j=0}^{1}\pi_{(i,j)}R_{(i,j)}(a) + \beta\sum_{k=0}^{K}\sum_{l=0}^{K}V^*\left(T\left(\Pi, a, (k,l)\right)\right)\times Pr\left\{(k,l)|\Pi, a\right\}\right\} \tag{4}$$

or receive traffic. The energy consumption model in [12] is used to evaluate the consumed energy of each operation mode.

Since the coverage of CRSN is much smaller than the transmission range of PU, the received PU signal power at each sensor node is assumed to be the same. When the received PU power on the bandwidth of 6 MHz is given as a parameter value, on one third of the PU signal power is assumed to be collected at each sensor node since the bandwidth of CRSN is 2 MHz.

In the simulation, $T_s = 2$ ms, $N_0 = -163$ dBm/Hz, $\beta = 0.95$, and the quantization level $K = 20$. γ_1 and γ_{K-1} are decided to satisfy $v_0(0) = 0.001$ and $v_1(K-1) = 0.001$. Then, for $1 < k < K-1$, $\gamma_k = \gamma_1 + (k/(K-2))(\gamma_{K-1} - \gamma_1)$. Note that $\gamma_0 = -\infty$ and $\gamma_K = +\infty$.

We now examine the values of the immediate rewards used in the simulation. Considering that the data transmission on the channel where a PU exists (i.e., a PU-existence channel) should be avoided for PU protection but the transmission on the vacant channel needs to be encouraged, we set $r_{(1,\cdot)(\cdot,\cdot)}(DATA) = -10$ and $r_{(0,\cdot)(\cdot,\cdot)}(DATA) = 10$. On the other hand, sensing the vacant channel should be discouraged for preventing the energy waste due to unnecessary sensing. We determine the reward for sensing the vacant channel, based on the consumed energy in the corresponding operation mode. Let E_a denote the total consumed energy of the CRSN in the operation mode a. When applying the energy consumption model in [12], $r_{(0,\cdot)(\cdot,\cdot)}(SO) = -E_{\mathrm{SO}}/E_{\mathrm{SB}} = -1$, and $r_{(\cdot,0)(\cdot,\cdot)}(SB) = -E_{\mathrm{SB}}/E_{\mathrm{SB}} = -1$. Similarly, changing the vacant (PU-existence) channel to another vacant (PU-existence) channel incurs unnecessary energy consumption. Thus, $r_{(0,\cdot)(0,\cdot)}(CO) = r_{(1,\cdot)(1,\cdot)}(CO) = -E_{\mathrm{CO}}/E_{\mathrm{SB}} \simeq -2.5$, and $r_{(\cdot,0)(\cdot,0)}(CB) = r_{(\cdot,1)(\cdot,1)}(CB) = -E_{\mathrm{CB}}/E_{\mathrm{SB}} = -1$. In addition, since changing the vacant channel to a PU-existence channel is much worse than moving between the channels in the same state, we assign the additional penalty, which is denoted by ξ_c, to change the vacant channel to a PU-existence channel. Thus, $r_{(0,\cdot)(1,\cdot)}(CO) = \xi_c \times r_{(0,\cdot)(0,\cdot)}(CO)$, and $r_{(\cdot,0)(\cdot,1)}(CB) = \xi_c \times r_{(\cdot,0)(\cdot,0)}(CB)$. In simulation, $\xi_c = 2$. Thus, $r_{(0,\cdot)(1,\cdot)}(CO) = -5$, and $r_{(\cdot,0)(\cdot,1)}(CB) = -2$.

On the other hand, sensing a PU-existence channel is likely to be desirable for fast PU detection. Furthermore, since the operating channel needs to be treated more importantly than the backup channel, we assign a weight w_O to the operating channel. That is, $r_{(1,\cdot)(\cdot,\cdot)}(SO) = w_O \times r_{(\cdot,1)(\cdot,\cdot)}(SB)$. In addition, for PU protection, changing a PU-existence channel to a vacant channel can be the more urgent operation than simply sensing the PU-existence channel for PU protection. To reflect this urgency, we introduce another weight w_C for channel changing. Then, $r_{(1,\cdot)(0,\cdot)}(CO) = w_C \times r_{(1,\cdot)(\cdot,\cdot)}(SO)$, and $r_{(\cdot,1)(\cdot,0)}(CB) = w_C \times r_{(\cdot,1)(\cdot,\cdot)}(SB)$. In simulation, $w_O = 5$, $w_C = 2$, and $r_{(\cdot,1)(\cdot,\cdot)}(SB) = 1$. Then, $r_{(1,\cdot)(\cdot,\cdot)}(SO) = 5$, $r_{(1,\cdot)(0,\cdot)}(CO) = 10$, and $r_{(\cdot,1)(\cdot,0)}(CB) = 2$.

B. Simulation Results

The PU disturbance ratio, which is defined as the time portion that a PU-existence channel is used for traffic transmission of the CRSN during the sojourn time of PU on the channel, and the ratio of the energy consumed for channel sensing/switching to the total consumed energy are used as the performance measures. We first evaluate in Fig. 2 the effect that the PU active/inactive duration and the number of sensor nodes have on the performance of the proposed scheme. In the figure, the received PU power on 6 MHz is set to -114 dBm, and the active duration of a PU on a channel $1/\lambda$ is three times longer than the inactive duration $1/\mu$. We can see in Fig. 2 that the performance is improved with more nodes. This is because the CH more exactly estimates the channel state by combining the sensing results of more nodes. In addition, since the CRSN can obtain better performance when the channel state changes more slowly, the performance of CRSN gets better with the longer PU active/inactive period, as seen from Fig. 2.

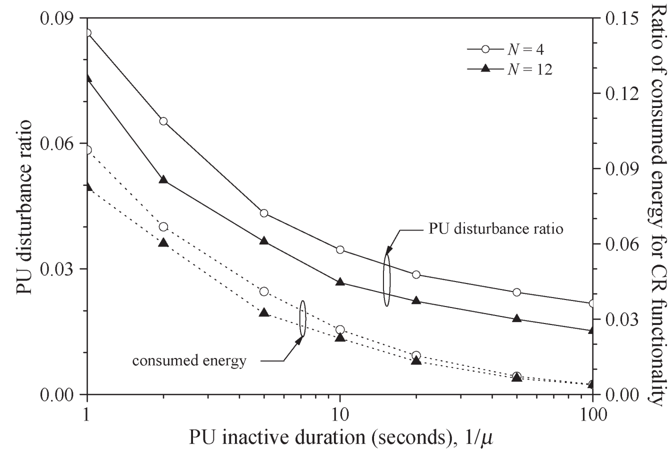

Fig. 2. Performance of the proposed scheme according to PU inactive duration.

Next, we compare the performance of the proposed scheme with that of a fixed sensing period scheme, which senses the operating and backup channels with their respective fixed periods. First, we shortly describe the fixed sensing period scheme. The CRSN with the fixed sensing period scheme senses the operating (backup) channel after performing the $DATA$ mode ζ (2ζ) times. At channel sensing, a sensor node measures the received signal energy on the sensing channel and reports it to the CH. When the sum of the signal energies reported from all sensor nodes is larger than the detection threshold, the CH determines that a PU exists on the corresponding channel and immediately orders the cluster members to move to the backup channel. For the given received PU power, the detection threshold is determined so that the false alarm probability is equal to the PU miss-detection probability.

Fig. 3 shows the performance comparison results between the proposed scheme and the fixed sensing period scheme, where $1/\lambda = 30$ s, $1/\mu = 10$ s, and $N = 8$. We can observe from Fig. 3 that the proposed scheme provides the PU disturbance ratio as low as a fixed sensing period scheme with $\zeta = 30$ while consuming much less energy. In addition, when comparing with the fixed sensing period scheme with $\zeta = 50$, the proposed scheme can more effectively protect the PU with almost the same consumed energy. The reason is given as follows: Since the proposed scheme manages the information vector tracing the channel states with the history of sensing outcomes, it can more exactly estimate the states of operating and backup channels. As a result, based on the channel states more accurately estimated, the proposed scheme senses more often the channel where a PU is likely to be activated, and when a PU appears on the operating channel, it moves to the vacant backup channel faster. Furthermore, the proposed scheme tries to reduce unnecessary channel sensing and switching by assigning the negative rewards to sensing and changing of vacant channels. Thus, the proposed scheme consumes less energy for CR-inherent operations than the fixed sensing period scheme, which periodically senses the channels and unconditionally carries out channel switching for a detection alarm from one sensing.

V. Conclusion

We have proposed an adaptive channel management scheme for the CRSN, which optimally selects the operation mode based on the

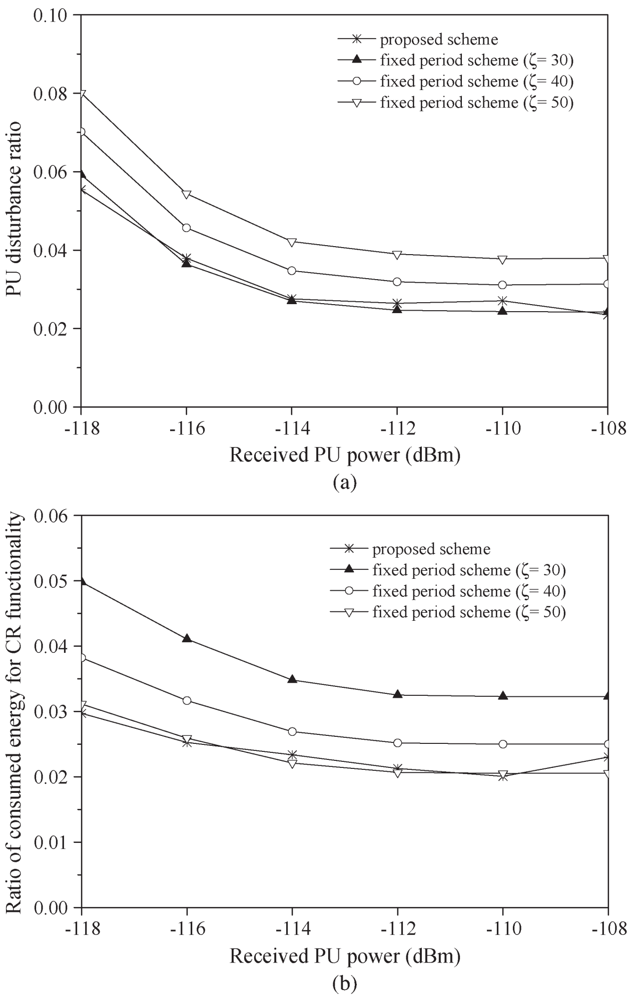

Fig. 3. Performance comparison between the proposed scheme and the fixed sensing period scheme. (a) PU disturbance ratio. (b) Ratio of consumed energy for CR functionality.

POMDP framework. Even though the CRSN does not exactly know channel states due to random noise, it can determine the optimal operation mode with the proposed scheme. Furthermore, the proposed scheme can be easily implemented since the CH selects the operation mode from the policy, which is precomputed and stored to the CH. By using the simulation, we have shown that the proposed scheme lessens the energy consumption while providing a high level of PU protection. Consequently, by adopting the proposed scheme, a CRSN can utilize temporarily vacant channels with only a small burden of energy consumption and with low computational complexity.

References

[1] D. Puccinelli and M. Haenggi, "Wireless sensor networks: Applications and challenges of ubiquitous sensing," *IEEE Circuits Syst. Mag.*, vol. 5, no. 3, pp. 19–31, Sep. 2005.

[2] G. Zhou, J. A. Stankovic, and S. H. Son, "Crowded spectrum in wireless sensor networks," in *Proc. EmNets*, Cambridge, MA, May 2006.

[3] O. Akan, O. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Netw.*, vol. 23, no. 4, pp. 34–40, Jul. 2009.

[4] Z. Liang and D. Zhao, "Quality of service performance of a cognitive radio sensor network," in *Proc. IEEE ICC*, Cape Town, South Africa, May 2010.

[5] S. Feng and D. Zhao, "Supporting real-time CBR traffic in a cognitive radio sensor network," in *Proc. IEEE WCNC*, Sydney, Australia, Apr. 2010.

[6] S. Izumi, K. Tsuruda, T. Takeuchi, H. Lee, H. Kawaguchi, and M. Yoshimoto, "A low-power multi resolution spectrum sensing architecture for a wireless sensor network with cognitive radio," in *Proc. SENSORCOMM*, Athens/Glyfada, Greece, Jun. 2009.

[7] W. Xia, S. Wang, W. Liu, and W. Cheng, "Cluster based energy efficient cooperative spectrum sensing in cognitive radios," in *Proc. WiCom*, Beijing, China, Sep. 2009, pp. 1641–1644.

[8] S. Maleki, A. Pandharipande, and G. Leus, "Energy efficient distributed spectrum sensing for cognitive sensor networks," *IEEE Sensors J.*, vol. 11, no. 3, pp. 565–573, Mar. 2011.

[9] S. Gao, L. Qian, and D. R. Vaman, "Distributed energy efficient spectrum access in cognitive radio wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5205–5213, Oct. 2009.

[10] G. E. Monahan, "A survey of partially observable Markov decision processes: Theory, models, and algorithms," *Manage. Sci.*, vol. 28, no. 1, pp. 1–16, Jan. 1982.

[11] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proc. IEEE*, vol. 55, no. 4, pp. 523–531, Apr. 1967.

[12] J. Polastre, R. Szewczyk, and D. Culler, "Telos: Enabling ultra-low power wireless research," in *Proc. IPSN/SPOTS*, Los Angeles, CA, Apr. 2005, pp. 364–369.

Closed-Form Level Crossing Rates Expressions of Orthogonalized Correlated MIMO Channels

Predrag Ivanis, *Member, IEEE*,
Vesna Blagojevic, *Student Member, IEEE*,
Dusan Drajic, *Life Member, IEEE*, and
Branka Vucetic, *Fellow, IEEE*

***Abstract*—In this paper, the exact closed-form expressions for the level crossing rate (LCR) and the temporal autocorrelation function (ACF) of the signal-to-noise ratio (SNR), at the output of the spatially correlated multiple-input–multiple-output (MIMO) systems with orthogonal space-time block codes (OSTBCs), are derived. The expressions are derived for the case of an arbitrary number of Rayleigh distributed branches and any form of the covariance matrix. The derived identities can be applied to isotropic and nonisotropic scattering environments, and they are validated by Monte Carlo simulations.**

***Index Terms*—Autocorrelation function (ACF), level crossing rate (LCR), multiple input multiple output (MIMO), Rayleigh fading, space-time coding.**

I. Introduction

It is well known that the theoretical capacity of a multiple-input–multiple-output (MIMO) channel can be approached if it is transformed into mutually separated eigenchannels [1]. As the signal-to-noise ratio (SNR) at the eigenchannel outputs is a time-varying random process, it can be described by using the probability density function (pdf) and the level crossing rate (LCR) derived in [2] and [3],

Manuscript received July 20, 2010; revised December 3, 2010 and February 8, 2011; accepted February 17, 2011. Date of current version May 16, 2011. This work was supported by the Serbian Ministry of Science under Technology Development Project TR32028 "Advanced Techniques for Efficient Use of Spectrum in Wireless Systems." The review of this paper was coordinated by Prof. J. Chun.

P. Ivanis, V. Blagojevic, and D. Drajic are with the Faculty of Electrical Engineering, University of Belgrade, 11020 Belgrade, Serbia (e-mail: predrag.ivanis@etf.rs).

B. Vucetic is with the School of Electrical and Information Engineering, University of Sydney, NSW 2006, Australia.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2011.2129546

0018-9545/$26.00 © 2011 IEEE