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• **Supplementary File** •

Novel Spectrum Sensing and Access in Cognitive Radio Networks

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Appendix A Eliminating algorithm of self-interference

In order to clear up the self-interference, the secondary users (SUs) should estimate the self-interference and remove it from the signal received. Suppose that the signal estimated for the self-interference is $k_a s(t)$, where k_a is the attenuation coefficient of the estimator, $s(t)$ is the local transmitted signal of the SU. When subtracting the estimated signal from the received signal $r(t)$, we would send the signal to the detector to decide whether the PU is present or not. The self-interference eliminating discussed in the paper can be described as in Figure A1. The attenuation coefficient of the estimator can be obtained by the iteration as follows

$$k_a(m) = k_a(m-1) + \Delta R_{ys}(0) \tag{A1}$$

where

$$R_{ys}(0) = \int_0^T y(t)s(t)dt \tag{A2}$$

is the cross correlation function between the detected signal $y(t)$ and the local transmitted signal $s(t)$ at the same time.

Then, the eliminating algorithm of self-interference, which is based on the least mean square criterion, can be summarized as in Algorithm A1.

Algorithm A1 : Eliminating Algorithm of Self-Interference

1: Initialization, set $k_a(0) = 0$;
2: The m^{th} iteration process:
Calculate the estimated signal of the transmitted signal of the SU, $s'(t) = k_a(m)s(t)$;
3: Subtract the estimated signal $s'(t)$ from the signal received of the SU $r(t)$ and obtain the detected signal $y(t) = r(t) - s'(t)$;
4: Calculate the cross correlation function between $y(t)$ and $s(t)$, $R_{ys}(0)$;
5: For the given iterative step size Δ, update the attenuation coefficient of the estimator $k_a(m)$ according to (A1);
6: Send $y(t)$ to the detector to detected whether the PU is present or not. We may use any spectrum sensing algorithm we want to detect the PU signal;
7: Go back to *Step* 2 until the data transmission of SU is finished;
8: End.

Appendix B Performances analysis

In this section, we discuss the performance of our proposed CR network in which the spectrum sensing and access operate simultaneously (SSAOS), and compare it with the conventional CR network.

Suppose there are I primary user (PUs) and J SUs in a cognitive radio (CR) network, in which there are N subchannels with bandwidth B. The traffic arrivals of PUs and SUs follow the Poisson processes with mean rates λ_p ($\lambda_p > 0$) and λ_s ($\lambda_s > 0$), and their service periods follow the negative exponential distributions with mean rates μ_p and μ_s respectively.

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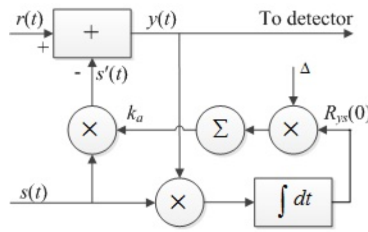

Figure A1 Block diagram of estimator.

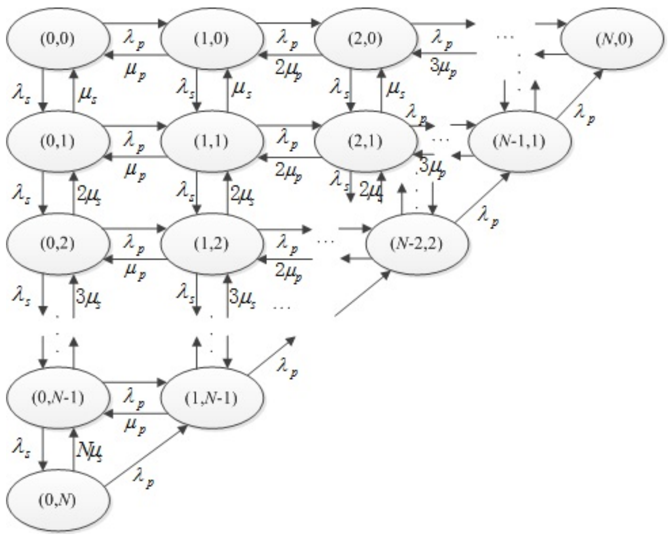

Figure B1 Model of access of PUs and SUs in CR networks.

The SUs adopt the spectrum access switch strategy in which the SUs switch to another new "spectrum hole" when any PU is present in the subchannel. Therefore, the sensing and access of PUs and SUs can be modeled as a state transition model shown in Figure B1, where the state (i,j) represents the state where there are i active PUs and j active SUs in the cognitive network, $i \leqslant I,\ j \leqslant J$. Because there are only N subchannels in the cognitive network, the state space should satisfy the constraint as follows

$$\Omega = \{(i,j):\ 0 \leqslant i \leqslant N,\ 0 \leqslant j \leqslant N,\ 0 \leqslant i+j \leqslant N\} \tag{B1}$$

When $i+j \leqslant N-1,\ j \geqslant 1$, there are some free subchannels to be accessed in the network. If a PU presents, the state will transfer from (i,j) to $(i+1,j)$ with the state transition probability λ_p. If an SU is allowed to access the network, the state will transfer from (i,j) to $(i,j+1)$ with the transition probability λ_s. When $i+j=N,\ j \geqslant 1$, there is no any free subchannel to be accessed. At this moment, if a PU is present, the SU should release the subchannel occupied. And then, the state will transfer from (i,j) to $(i+1,j-1)$ with the probability λ_p. If a SU wants to access the network, it has to wait until there is a subchannel released by a PU or other SUs in the network.

Throughput. Assuming the data transmission period of the l^{th} SU is $T_l, 1 \leqslant l \leqslant j$, the throughput of SU's CR network can be given by

$$throuhput = B\sum_{j=1}^{N}\sum_{l=1}^{j} T_l \sum_{i=0}^{N-j} \pi_{i,j} \tag{B2}$$

where $\pi_{i,j}$ is the probability of state (i,j) in the network.

The Markov process in Figure B1 can be taken as the Quasi-Birth-and-Death process with the generator matrix as follows [1]

$$\mathbf{Q} = \begin{bmatrix} \mathbf{A}_0 & \mathbf{C}_0 & 0 & \cdots & 0 \\ \mathbf{B}_1 & \mathbf{A}_1 & \mathbf{C}_1 & \cdots & 0 \\ 0 & \mathbf{B}_2 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \mathbf{A}_{N-1} & \mathbf{C}_{N-1} \\ 0 & 0 & \cdots & \mathbf{B}_N & \mathbf{A}_N \end{bmatrix} \tag{B3}$$

Where,

$$\mathbf{A}_k = \begin{bmatrix} a_1 & \lambda_s & 0 & \cdots & 0 \\ \mu_s & a_2 & \lambda_s & \cdots & 0 \\ 0 & 2\mu_s & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & a_3 & \lambda_s \\ 0 & 0 & \cdots & (N-k)\mu_s & a_4 \end{bmatrix} \quad 0 \leqslant k \leqslant N-1 \tag{B4}$$

where

$$a_1 = -(\lambda_s + \lambda_p + k\mu_p) \tag{B5}$$

$$a_2 = -(\lambda_s + \lambda_p + \mu_s + k\mu_p) \tag{B6}$$

$$a_3 = -(\lambda_s + \lambda_p + (N-1-k)\mu_s + k\mu_p) \tag{B7}$$

$$a_4 = -(\lambda_p + (N-k)\mu_s + k\mu_p) \tag{B8}$$

and

$$\mathbf{A}_N = -N\mu_p \tag{B9}$$

$$\mathbf{B}_k = k\mu_p \mathbf{I}_{N+1-k},\ 1 \leqslant k \leqslant N \tag{B10}$$

$\mathbf{I}_{N+1-k}$ is the identity matrix of order $(N+1-k)$, and

$$\mathbf{C}_k = \begin{bmatrix} \lambda_p & 0 & 0 & \cdots & 0 \\ 0 & \lambda_p & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \lambda_p & 0 \\ 0 & 0 & \cdots & 0 & \lambda_p \\ 0 & 0 & \cdots & 0 & \lambda_p \end{bmatrix} \quad 0 \leqslant k \leqslant N-1 \tag{B11}$$

For the Quasi-Birth-and-Death process, according to Netus theory, we have

$$\boldsymbol{\pi}\mathbf{Q} = \mathbf{0} \tag{B12}$$

where

$$\boldsymbol{\pi} = \left[\boldsymbol{\pi}_{0,0}\ \boldsymbol{\pi}_{0,1}\ \cdots\ \boldsymbol{\pi}_{0,N}\ \boldsymbol{\pi}_{1,0}\ \boldsymbol{\pi}_{1,1}\ \cdots\ \boldsymbol{\pi}_{1,N-1}\ \cdots\ \boldsymbol{\pi}_{N,0}\right] \tag{B13}$$

Then,we can get all of the state probabilities from

$$\begin{aligned} &\boldsymbol{\pi}\mathbf{Q} = \mathbf{0} \\ &s.t.\ \ \Sigma_{i=0}^{N}\Sigma_{j=0}^{N-i}\pi_{i,j} = 1. \end{aligned} \tag{B14}$$

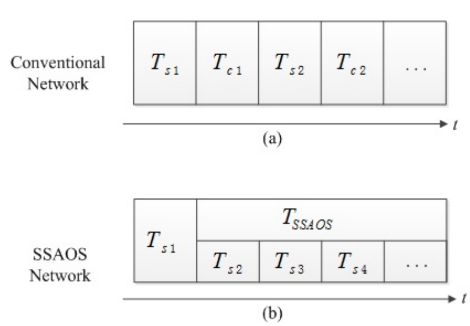

Figure B2 Sensing and access slots in CR networks.

(B14) is the boundary condition of steady state of Quasi-Birth-and-Death process. From (B2), we know that the data transmission period of SUs, T_l, is an important factor which affects the network throughput. Figure B2 shows the difference of the data transmission periods between SSAOS CR networks and conventional ones when there are idle subchannels. In SSAOS CR networks, the spectrum sensing and access operate simultaneously except for the first slot T_{s1}). But in the network, the spectrum sensing and access operate separately, sensing slots (T_{s1}, T_{s2}, $\cdots$) and access slots (T_{c1}, T_{c2}, $\cdots$) are alternate in time. In any slot, only one operation, sensing or access, can be carried out.Therefore, the data transmission period in SSAOS CR networks is much longer than that in the conventional ones. The throughput of SSAOS networks should be much larger than that of the conventional ones.

Delay. The delay is defined as the time for which a SU waits to access an idle subchannel if it wants to access the network.

In the conventional CR network, if a SU wants to access the network, it will first sense the surrounding spectrum, and then decide whether there is any idle subchannel to be accessed. If there is an idle subchannel ($i+j < N$), it can immediately access one of the idle subchannels. If there is no any idle subchannels ($i+j = N$), it should wait until PUs or other SUs releases a subchannel. Therefore, the average access delay of the conventional cognitive network can be expressed as follows

$$t_c = T + \sum_{i=0,\ j=N-i}^{N} \pi_{i,j}[\min\{t_{ps}, t_{ss}\} + T] \tag{B15}$$

where T is the sensing period, t_{ps} and t_{ss} are the service periods of the PU and SU respectively, which follow the negative exponential distributions with mean rates μ_p and μ_s; $\min\{t_{ps}, t_{ss}\}$ denotes to take the smaller between t_{ps} and t_{ss}.

In the SSAOS cognitive network, SUs continuously sense the spectrum and are aware of the subchannel states in real time. The delay can be formaulted as follows

$$t_s = \sum_{i=0,\ j=N-i}^{N} \pi_{i,j}[\min\{t_{ps}, t_{ss}\} + T] \tag{B16}$$

Obviously, the delay in the SSAOS cognitive network is much shorter than that in the conventional one.

Collision Probability. When a PU wants to access a subchannel which has been occupied by a SU, a transmission collision between the SU and PU will occur. The collision probability between the SU and PU is the condition probability in which a PU is present in the subchannel which has been occupied by an SU.

First, we formulate the access probability of a SU. SUs may access a subchannel in two cases. One is the case when a PU is present but has not been detected; another is the case when a PU is absent and has not been detected in practice. Then, the access probability of a SU is given by

$$P_a = \lambda_p(1 - P_d) + (1 - \lambda_p)(1 - P_{fa}) \tag{B17}$$

where P_d is the probability of detection and P_{fa} is the probability of false alarm.

Now, we reckon the access probability of a PU. Note that the access slots of PUs in SSAOS CR networks are very different from those in the conventional ones, as showed in Figure B3.

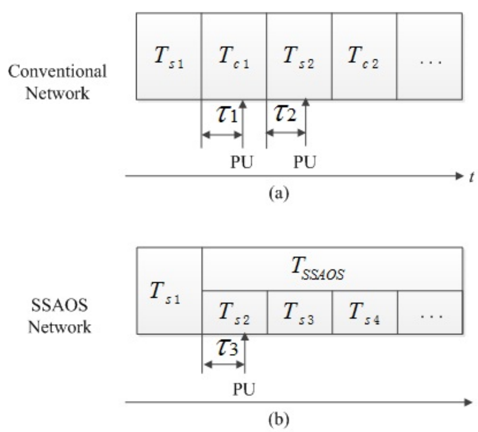

Figure B3 Access slots of PUs in CR networks.

In the conventional CR networks, PU may access a subchannel in both the sensing slots and access slots of SUs. In the sensing slots, the access probability of a PU is given by

$$P_1 = \int_0^{T_s} \lambda_p(1 - P_d)\frac{1}{T_s}d\tau_2 = \lambda_p(1 - P_d) \tag{B18}$$

In the access slots, the access probability of a PU is given by

$$P_2 = (1 - \lambda_p)(1 - P_{fa})\int_0^{T_c} e^{-\mu_s\tau_1}d\tau_1 = (1 - \lambda_p)(1 - P_{fa})(1 - e^{-\mu_s T_c}) \tag{B19}$$

where T_c is the access period of SUs.

Therefore, the transmission collision probability between the SU and PU can be expressed as follows

$$P_c = \frac{P_1 + P_2}{P_a} = \frac{\lambda_p(1 - P_d) + (1 - \lambda_p)(1 - P_{fa})(1 - e^{-\mu_s T_c})}{\lambda_p(1 - P_d) + (1 - \lambda_p)(1 - P_{fa})} \tag{B20}$$

In the SSAOS cognitive network proposed, SUs sense the spectrum continuously. All slots are taken as sensing slots. So, the access probability of a PU can be obtained by

$$P_3 = \int_0^{T_s} \lambda_p(1-P_d)\frac{1}{T_s}d\tau_3 = \lambda_p(1-P_d) \tag{B21}$$

Then, the transmission collision probability can be given by

$$P_s = \frac{P_3}{P_a} = \frac{\lambda_p(1-P_d)}{\lambda_p(1-P_d)+(1-\lambda_p)(1-P_{fa})} \tag{B22}$$

From (B20) and (B22), it can be seen that the collision probability in the cognitive network proposed will be smaller than that in the conventional network.

References

1 Zhang H B. Theory and applications of T-QBD process. Shanghai: Ph.D Dissertation, Shanghai University, 2010.