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Novel spectrum sensing and access in cognitive radio networks

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Dear editor,
The throughput, delay and collision probability between the primary users (PUs) and secondary users (SUs) have been considered as the main performance measures in cognitive radio (CR) networks [1]. The longer the sensing period, the more accurate the spectrum sensing. But a longer sensing period will result in lower system throughput. On the other hand, the shorter the sensing period, the greater the throughput of CR networks, and the less accurate the spectrum sensing. It will result in more collisions and interference between PUs and SUs, and degrade the performances of both PUs and SUs.

Recently, a full duplex spectrum sensing technique was proposed to improve the performances [2], in which SUs can sense the licensed spectrum simultaneously when transmitting data. In order to eliminate the self-interference caused by the local transmitters in SUs, some self-interference cancelling technologies, such as antenna cancellation scheme [3], antenna isolation technology [4], and adaptive medium access control protocol [5,6], were proposed. Some parameters in the schemes are related to the RF of CR signal. If the radio frequency (RF) of CR signal is fixed, these schemes are practically feasible. Unfortunately, the RF of CR signal is variable. When SUs access the channel, the RF of CR signal depends on the position of the spectrum hole, which is random.

To address the problems, we propose a novel spectrum sensing and access scheme to achieve continuous spectrum sensing and access. Based on the independence between the SU's signal and PU's signal, the self-interference of the local transmitter to the receiver in SUs is estimated and removed. It is indicated that the scheme proposed provides a distinctive advantage over the conventional one in the throughput, delay and collision probability.

System model. Assume that there is one PU and one SU in the CR network. The transmitter and receiver in the SU work simultaneously. When the SU transmits its signal, it also senses its surrounding spectrum. The signal received in the SU is given by

$$r(t) = h_{\mathrm{tr}} s(t) + p(t) + n(t), \tag{1}$$

where $s(t)$ is the local transmitted signal of the SU, $p(t)$ is the transmitted signal of the PU, $n(t)$ is Gaussian noise in the network, h_{tr} is the attenuation factor of the channel between the transmitter and receiver in the transceiver of the SU, $0 \leqslant t \leqslant T$, T is the period of the spectrum sensing.

When the SU finds any idle spectrum, it will access the spectrum to transmit its data. In this case, the hypothesis test of whether the spectrum is idle or not can be formulated as a binary hy-

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pothesis testing as follows:

$$\begin{cases} H_0 : r(t) = h_{\rm tr}s(t) + n(t), \\ H_1 : r(t) = h_{\rm tr}s(t) + p(t) + n(t), \end{cases} \tag{2}$$

where H_0 is the hypothesis when PU is absent, H_1 is the hypothesis when PU is present.

It is obvious that the self-interference, $h_{\rm tr}s(t)$, would interfere in the detection of the PU signal. Since the transmitter and receiver are together in the SU, we can estimate the self-interference from the transmitter and remove it from the received signal.

Elimination of self-interference. Suppose that the signal estimated for the self-interference is $k_{\rm a}s(t)$, where $k_{\rm a}$ is the attenuation coefficient of the estimator. When subtracting the estimated signal from the received signal $r(t)$, we would obtain the signal, which can be sent to the detector to decide whether the PU is present or not, as follows:

$$y(t) = h_{\rm tr}s(t) + p(t) + n(t) - k_{\rm a}s(t). \tag{3}$$

The cross correlation function between $y(t)$ and $s(t)$ can be expressed as

$$R_{ys}(\tau) = \int_0^T y(t)s(t+\tau){\rm d}t. \tag{4}$$

Since the transmitted signal of the SU, $s(t)$, is uncorrelated to the transmitted signal of the PU, $p(t)$, and the Gaussian noise, $n(t)$, the cross correlation function between $p(t)$ and $s(t)$ as well as the cross correlation function between $n(t)$ and $s(t)$ are zero. Then, the cross correlation function $R_{ys}(\tau)$ can be rewritten as

$$R_{ys}(\tau) = (h_{\rm tr} - k_{\rm a})R_{ss}(\tau), \tag{5}$$

where

$$R_{ss}(\tau) = \int_0^T s(t)s(t+\tau){\rm d}t. \tag{6}$$

Letting $\tau = 0$, we have

$$R_{ys}(0) = (h_{\rm tr} - k_{\rm a})R_{ss}(0). \tag{7}$$

On the other hand, the estimated error of self-interference can be expressed as follows:

$$\varepsilon = h_{\rm tr}s(t) - k_{\rm a}s(t) = (h_{\rm tr} - k_{\rm a})s(t). \tag{8}$$

Note that $R_{ss}(0)$ is the average power of $s(t)$. $R_{ss}(0) > 0$ for any stochastic signal $s(t)$ only when $s(t) \equiv 0$. Comparing (5) and (8), we find $R_{ys}(0) = 0 \Leftrightarrow k_{\rm a} = h_{\rm tr} \ \Leftrightarrow \ \varepsilon = 0$. That is, when and only when $R_{ys}(0) = 0$, we can estimate the self-interference accurately, i.e., $k_{\rm a}s(t) = h_{\rm tr}s(t)$. Therefore, we can use the cross correlation function $R_{ys}(0)$ as the estimated error of the self-interference to adjust the iterative coefficient of the adaptive estimator. When the mean square of $R_{ys}(0)$ is the smallest, the mean square of the estimated error of the self-interference would be the smallest. When the mean square of $R_{ys}(0)$ is equal to zero, the mean square error would be also equal to zero. At this point, we can suppress the self-interference from the received signal completely. The signal processed $y(t)$, in which there is no self-interference, can be sent to the detector to detect whether the PU is present or not. Therefore, the problem of suppressing the self-interference may be formulated as the following optimization:

$$\min_{k_{\rm a}} \ (h_{\rm tr} - k_{\rm a})^2 \Leftrightarrow \min_{k_{\rm a}} \ R_{ys}^2(0). \tag{9}$$

It is strictly a convex optimization. By utilizing the Lagrange multiplier method, we are able to obtain the globally optimal solution as follows:

$$k_{\rm a} = h_{\rm tr}. \tag{10}$$

Thus, the attenuation coefficient of the estimator, $k_{\rm a}$, can be obtained by the iteration as follows:

$$k_{\rm a}(m) = k_{\rm a}(m-1) + \Delta R_{ys}(0), \tag{11}$$

where Δ is the iterative step size.

Performances analysis. The throughput of the CR network, the delay of the CR signal as well as the collision probability between SUs and PUs are the main aspects to evaluate the performance of CR networks. In the following, we will briefly analyze the throughput, delay and collision probability.

(1) Throughput. It is well known that the data transmission period of SUs is an important factor which affects the network throughput. In our proposed CR network, the spectrum sensing and access operate simultaneously except for the first slot. While the SU senses its surrounding spectrum, it can also transmit its signal. In the conventional one, the spectrum sensing and access operate separately. The sensing slots and access slots are alternate in time. In any slot, only one operation, sensing or access, can be carried out. Therefore, the throughput of network proposed is much larger than that of the conventional one.

(2) Delay. The delay is defined as the time for which an SU waits to access an idle subchannel if it wants to access the network. In the conventional CR network, if an SU wants to access the network, it will first sense the surrounding spectrum and then decide whether to access. If there is an idle subchannel, it can immediately access one of the

idle subchannels. If there is no any idle subchannels, it should wait until PUs or other SUs releases a subchannel. Suppose there are N subchannels, the average access delay of the conventional CR network can be expressed as follows:

$$t_{\rm c} = T + \sum_{i=0,\ j=N-i}^{N} \pi_{i,j}[\min\{t_{ps}, t_{ss}\} + T], \quad (12)$$

where $\pi_{i,j}$ is the probability of state (i,j) in the CR network, t_{ps} and t_{ss} are the service periods of the PU and SU respectively, $\min\{t_{ps}, t_{ss}\}$ denotes the smaller in t_{ps} and t_{ss}.

In our proposed network, SUs continuously sense the spectrum and are aware of the subchannel states in real time. The delay can be formulated as follows:

$$t_{\rm s} = \sum_{i=0,\ j=N-i}^{N} \pi_{i,j}[\min\{t_{ps}, t_{ss}\} + T]. \quad (13)$$

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

(3) Collision probability. When a PU wants to access a subchannel which has been occupied by an 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. In the conventional CR network, PU may access a subchannel in both the sensing slots and access slots of SUs. The collision probability is given by

$$P_{\rm c} = \frac{\lambda_{\rm p}(1-P_{\rm d}) + (1-\lambda_{\rm p})(1-P_{\rm fa})(1-{\rm e}^{-\mu_{\rm s}T_c})}{\lambda_{\rm p}(1-P_{\rm d}) + (1-\lambda_{\rm p})(1-P_{\rm fa})}. \quad (14)$$

where $\lambda_{\rm p}$ is the Poisson arrival rate of PUs, $\mu_{\rm s}$ is the mean rate of the service period for USs, $P_{\rm d}$ is the probability of detection and $P_{\rm fa}$ is the probability of false alarm, T_c is the access period of SUs.

In the proposed network, SUs sense the spectrum continuously. All slots are taken as sensing slots. The collision probability can be given by

$$\begin{aligned} P_s &= \frac{P_3}{P_a} \\ &= \frac{\lambda_{\rm p}(1-P_{\rm d})}{\lambda_{\rm p}(1-P_{\rm d}) + (1-\lambda_{\rm p})(1-P_{\rm fa})}. \end{aligned} \quad (15)$$

From (14) and (15), it is easily seen that the collision probability in the proposed CR network will be much smaller than that in the conventional one.

Conclusion. In this study, we have proposed a novel spectrum sensing and access scheme to solve the contradiction between the spectrum sensing time and throughput, in which the spectrum sensing and spectrum access work simultaneously. We obtained the maximum throughput of CR networks, minimum interference of SUs to PUs and lowest access delay of SUs. By estimating the transmitted signal of SUs, the self-interference of the local transmitter to the receiver in SUs is removed. The analysis shows that the scheme proposed has the obvious advantage over the conventional one in the throughput, delay and collision probability. Unlike the self-interference eliminating technologies based on antennas, our self-interference eliminating scheme is independent of the RF of CR signals to be transmitted. It makes the scheme more practical than others.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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