Cooperative Spectrum Sensing with Transmit and Relay Diversity in Cognitive Radio Networks

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**Summary**

The authors investigate the problem of cooperative spectrum sensing in cognitive radio (CR) networks over Rayleigh fading environment. The performance is analyzed by studying the error effects on the decision reporting and the results show that the cooperative spectrum sensing performance is limited by the probability of reporting errors.

To deal with the above problem, the authors propose a transmit diversity based cooperative spectrum sensing method over flat-fading and frequency-selective fading channels. Moreover, when some CRs are in heavy shadowing, they propose a relay diversity based cooperative spectrum sensing method to increase the diversity of detection. It is shown that, when combined with algebraic coding, the relay diversity further improves the cooperative spectrum sensing performance.

**Introduction**

Cognitive radio has been proposed to deal with the spectrum scarcity and under-utilization [3], [4]. The purpose of CR is to use the spectrum holes without causing harmful interference to the primary user. A great challenge in CR networks is the hidden terminal problem which happens when the CR is shadowed or degraded with high path loss while the PU is still operating. In cooperative spectrum sensing, local spectrum sensing information from multiple CRs is combined to make a joint decision on PU detection. It has been shown that cooperative spectrum sensing greatly increases the probability of PU detection [5]-[9]. Cooperative spectrum sensing consists of two main stages, sensing (at the CRs) and reporting (to the base station (BS) or fusion center). Usually, the researchers consider a sensing channel with Rayleigh fading and AWGN noise but an error-free reporting channel [5]-[9], which is practically not applicable because the reporting channels are also subject to interference or noise.

In this paper, they consider a realistic scenario of both the sensing and reporting channels experiencing fading and noise. They show that the performance of cooperative spectrum sensing is limited by the imperfect reporting channels. The probability of false alarm (when the PU does not operate but the BS detects it as in operation) is shown to be lower bounded and the bound tends to increase with the increase in probability of reporting errors. To cope with this problem, they propose a transmit diversity based cooperative spectrum sensing scheme by applying the space-time (ST) coding and space-frequency (SF) coding schemes by viewing CRs as distributed antenna arrays. A relay diversity method with algebraic coding is also proposed to improve the performance of cooperative spectrum sensing when some CRs suffer heavy shadowing and are not able to forward their decisions to the BS directly.

**Cooperative Spectrum Sensing**

Consider a CR network that consist of *K* CRs (secondary users) and a common receiver which acts as a base station (BS) and manages the whole CR network, shown in Fig. 1.

The main task of spectrum sensing is to detect the presence of PU with little information about the channel. Energy detector is used in such scenarios which measures the energy of the received signal in a fixed bandwidth *W* over an observation time window of *T*. The performance of energy detector in AWGN channels was studied in [10], [11] and for a variety of fading channels in [5], [12], and [13].

In the presence of hidden terminal (when the CR is shadowed or in severe multipath fading), the CR assumes that the observed frequency band is vacant and starts using it, which causes harmful interference to the PU. To address this issue, multiple CRs can be coordinated to perform spectrum sensing cooperatively. Some recent research shows that cooperative spectrum sensing greatly increases the probability of detection in fading channels [5]-[8].

Generally, cooperative spectrum sensing consists of the following steps:

1. Every CR performs local sensing independently and then make a binary decision.
2. All of the CRs forward their binary decision to the BS.
3. The BS then combines all these decisions and makes a combined decision on the presence or absence of the PU.



Fig. 1. Cognitive Radio Network

**Performance Limits of Cooperative Spectrum Sensing**

Previous works assume an error-free reporting channel but practically it is impossible to transmit the decisions without error over the wireless channel. Thus, it is important to study the performance of cooperative spectrum sensing in realistic environments.

At first, a CR performs local spectrum sensing to get a local decision, *H0CR* or *H1CR*. Then the CR transmits its local decision to the BS via the reporting channel which is subject to fading and thus the information will be corrupted by fading and additive noise. The BS recovers and decodes the signal to get *H0BS* or *H1BS*.

*Definition:* The probability of reporting errors of the *i*th CR, denoted by *Pe,i*, is defined as the error probability of the signal transmission over the reporting channels between the *i*th CR and the common receiver.

Assume that the reporting channel is a binary symmetric channel (BSC) with an error probability *Pe,i*, which means that the probability of receiving *H1* (or *H0*) at the BS after the decision decoding, while *H0* (or *H1*) was transmitted is *Pe,i* for CR*i*.

*Theorem I:* Let *Qf* denote the probability of false alarm (PU is absent but is detected as present) and *Qm* denote the probability of missed detection (PU is present but is detected as absent) of cooperative spectrum sensing. Then,

 (1)

 (2)

where *Pf,i* and *Pm,i* are the false alarm and missed detection probabilities of the local spectrum sensing of the *i*th CR, respectively.

*Proof:* Using the property of Markov chain, we obtain,

 (3)

 (4)

Therefore,

 (5)

Likewise, we can get,

 (6)

Next, we consider a CR network with *K* CRs. Hence,

 (7)

By substituting (5) into (7), we get (1). Likewise,

 (8)

Substituting (6) into (8), we get (2).

*Corrolary I:* Suppose that the local spectrum sensing conducted by CR*i* results in *Pf,i = Pf* and *Pm,i = Pm* for all *i=1,…,K*, and that the probabilities of reporting errors are identical for all CRs, then

 (9)

Furthermore, *Qf* is bounded by,

 (10)

Fig. 2 shows the performance of cooperative spectrum sensing with respect to the number of CRs for an SNR dB and. It is seen that cooperative spectrum sensing with more CRs perform better in most cases but when *Qf* decreases to a threshold, namely the lower bound , the probability of missed detection *Qm* drastically increases to one which makes the detection probability *Qd* fall down to zero. Thus cooperative spectrum sensing is impractical when and increases with the increase in number of CRs, which is consistent with (10).



 Fig. 2. Performance for different number of CRs Fig.3 Performance for two CRs and different reporting error rates

Fig. 3 compares the performance results under different probability of reporting errors (*Pe*=10-1, 10-2, 10-3, 10-4) for two CRs and dB. It clearly demonstrates that the larger the probability of reporting errors, the larger the bound of *Qf*. *Qf* (probability of false alarm) can also be interpreted as bandwidth efficiency loss, we can see that the bandwidth efficiency loss increases with the increase of *Pe*.

**Cooperative Spectrum Sensing with Transmit Diversity**

In this section, transmit diversity is used to improve the performance of cooperative spectrum sensing by reducing *Pe*.

1. **Space-Time Coding for Cooperative Spectrum Sensing**

Assume that the local spectrum sensing has been completed at each node and that the local decisions are denoted by *D1* and *D2* for CR1 and CR2 respectively. Instead of transmitting *D1* and *D2* to the BS directly, the CRs are made to form a transmit cluster in which ST block coding can be applied in order to achieve spatial diversity. In order to implement distributed ST coding, we require that each CR sends its own decision to each other. If both CRs correctly decode the signals transmitted from each other, then ST coding can be applied. In this case, CR1 will send {*D1, D2*}, while CR2 will send {*-D2, D1*} to the BS. Otherwise, the CRs will continue to transmit their own decisions to the BS using the TDMA protocol. The time consumed in information exchange is ignored compared to the energy detection time.

In the proposed user cooperation protocol, the decisions are reported to the BS either directly in TDMA or by using ST coding based on the quality of reporting channel. Let *Ɛ* denote the error rate of the transmission over the inter-user channels between CR1 and CR2, and the error rate of BPSK using ST block coding and TDMA is denoted as *PeSTBC* and *PeTDMA*, respectively. Then the reporting error rate of the proposed user cooperation is given by,

 (11)

where denotes the probability of the two CRs both correctly decoding the received signal coming from each other. When the inter-user channel is very good, α approaches 1 and we have . This implies that the two CRs can always correctly decode the received signals due to the good inter-user channel and can achieve transmit diversity by using ST coding in the reporting process. Hence, diversity gain can be achieved and the reporting error probability can be reduced greatly. On the other hand, when the inter-user channel is poor, i-e when Ɛ=0.3 which corresponds to α = 0.5, *Pe* will be dominated by the term in (11). This shows that the reporting error rate performance has no diversity gain but is still better than TDMA.

Fig. 4 shows the performance comparison of cooperative spectrum sensing with two CRs for various inter-user channel qualities, *Ɛ* = 0, 0.01, 0.1, and 1. The sensing channels and reporting channels both experience Rayleigh fading with an average SNR dB and dB, respectively. It can be seen that STBC has a lower bound, which is 0.002, whereas it is 0.02 for TDMA.



Fig. 4. Performance of cooperative spectrum sensing for different channel qualities

1. **Space-Frequency Coding for Cooperative Spectrum Sensing**

An OFDM based CR system structure is considered. For OFDM based CRs, a few sub-channels are allocated for sending the local decisions to the BS. Each sub-channel is assigned exclusively to one CR and different CRs should transmit through orthogonal sub-channels to avoid interference from other CRs, which results in OFDMA. For instance the FDMA of two CRs can be described as,



As the CRs send their decisions through orthogonal sub-channels to the BS, FDMA cannot achieve the diversity gain.

SF coding has been shown to achieve both space and frequency diversity by spreading codewords over multiple transmit antennas and OFDM sub-channels [15], [17]. We regard the distributed CRs as a virtual antenna array and assume that the CRs can exchange their decisions. Instead of transmitting one symbol over one sub-channel only for a CR, we use SF coding over several OFDM sub-channels. An example of SF coding for two CRs is described as,



This shows that the decisions will be sent from two sub-channels simultaneously at each CR. This results in a frequency diversity of 2 over frequency-selective fading channels. This can help us reduce the reporting error probability and enhance cooperative spectrum sensing performance.

**Cooperative Spectrum Sensing with Relay Diversity**

Assume that CR*i* fails to send its decision *Di* to the BS due to heavy shadowing. Thus, this CR is useless for cooperative spectrum sensing and the maximum diversity gain is reduced. To exploit full diversity gain, the authors propose a *censor-and-relay* method.

If the SNR of the received signal from CR*i* is lower than a predefined threshold, then CR*i* will be labeled as an unreliable one. Then, the unreliable CR will be instructed to relay its local spectrum sensing result to other neighboring CRs which have good channel conditions. Once a neighboring reliable CR*j* is found, then CR*i* will forward its decision *Di* to CR*j*. In order to avoid the interference between the decision *Dj* and decision *Di*, CR*j* will forward the two decisions to the BS through two orthogonal sub-channels. Assume that CR*i* and CR*j* occupy sub-channel *Hj(mi)* and *Hj(mj)* to transmit the decisions to the BS, respectively, which is described as,



This shows that relay-assisted spectrum sensing is the same as FDMA with full cooperation. Suppose that *M* out of *K* CRs experience heavy shadowing. Without relaying, the spectrum sensing diversity order is (*K-M*). However, with the help of relay CRs, the maximum diversity order of *K* can be achieved by allocating all *K* decisions over *K* orthogonal sub-channels among the (*K-M*) reliable CRs.

The sensing diversity order of cooperative spectrum sensing in heavy shadowing can be improved by using some relay CRs but this results in the increase in lower bound as seen in (10). To decrease the lower bound  while achieving the maximum sensing diversity order, the authors propose an algebraic coding based approach to achieve signal space diversity for relay CRs.

Assume that CR*i* experiences heavy shadowing and CR*j* has a line-of-sight to the BS. In order to achieve the maximum sensing diversity, CR*i* will relay its decision *Di* to CR*j*. Then the decisions *Di* and *Dj* which are BPSK symbols are encoded as where is a 2x2 rotation matrix and *T* is the transpose operation. Subsequently, *Ci* and *Cj* are sent through orthogonal channels *Hj(mi)* and *Hj(mj)*, respectively, as



At the BS, the received symbols will be jointly decoded and the decoded decisions will be sent to the fusion center for decision making.

The rotation matrix can be carefully designed to achieve a full diversity of codewords over Rayleigh fading channels. This is known as signal space diversity. The authors exploit the signal space diversity and convert it into frequency diversity by transmitting two codewords through two orthogonal channels in the CR relay, which reduces the probability of reporting errors. Then, cooperative spectrum sensing can be further improved by lowering the bound.

Fig. 5 shows the performance of cooperative spectrum sensing with the proposed relay diversity and algebraic coding for two CRs. The sensing channels and reporting channels both experience Rayleigh fading with an average SNR dB and dB, respectively. The second CR is assumed to experience heavy shadowing in its reporting channel and cannot forward the decision to the BS. It can be seen that the curve without relay has the worst performance among the three examined cases at a large value of *Qf*, which shows that without relay, the sensing diversity order of cooperative spectrum sensing is lost. The other two curves have similar performance when *Qf* is larger than their lower bounds. This shows the benefit of using relaying but it can be seen that the lower bound  in the case of relay-only is larger than that in the case of without relay. This indicates that cooperative spectrum sensing with many CRs will induce an increase in the lower bound of *Qf* as shown in (10). The curve of relay with algebraic coding has the best performance and achieves both the sensing diversity order and the lower bound. This is because relay diversity allows us to achieve maximum sensing diversity order and algebraic coding results in lowering the bound of *Qf*.



Fig. 5. Cooperative spectrum sensing with relay diversity and algebraic coding

**Conclusion**

It was found that cooperative spectrum sensing with many CRs could increase the detection probability only within a limited range. To address the issue of performance limits, several robust cooperative spectrum sensing techniques, which apply transmit diversity with ST coding and SF coding in CR networks over fading channels, have been proposed. Finally, a relay diversity together with an algebraic coding method has been proposed when some CRs experience heavy shadowing, to greatly improve the performance of cooperative spectrum sensing.

**References**

\*The numbers shown in this summary are the same as the original paper reference numbers. Please refer to the paper for references.