

Cognitive Legacy Networks via Cooperative Diversity

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Abstract—In this letter, we deal with the cognitive radio (CR) concept for legacy primary links optimized for non-interference surroundings. In this type of network, primary destinations are not able to deal with possible interference and a missed cognitive detection significantly reduces the system performance. The enhancement of the primary network with cooperative diversity in addition to the well-known diversity gain for the primary link improves the sensing ability of the system and protects the primary user from possible interference. The proposed solution provides CR benefits without complicated network modifications and seems to be an attractive solution for future legacy networks.

Index Terms—Cooperative systems, relay channels, cognitive radio, legacy networks.

I. INTRODUCTION

IN contrast to previously reported work where Cognitive Radio (CR) [1] is designed as a global intelligent network [2], in this letter, we deal with the application of the CR in legacy primary networks. In these networks, primary links already exist and have been designed (optimized) for non-interference environments based on an older technology. Although cognitive destinations can use an advanced technology to mitigate possible interference (i.e. interference cancellation [3]), legacy primary links suffer from significant performance degradation in the case of a missed cognitive detection of the primary system. As the replacement (or update) of the pre-existing non-cognitive infrastructure is expensive and impractical, we are interested in solutions which can efficiently solve the above problem without complicated structural modifications.

In this letter, we investigate an efficient solution for the above problem based on the cooperative diversity concept [4]. Cooperative diversity provides spatial diversity benefits in single antenna systems and can be used as an efficient technique to combat interference in legacy cognitive scenarios. More specifically, the proposed solution enhances the primary legacy links with the assistance of a Decode-and-Forward (DF) relay [4]. The related diversity benefits not only improve the reliability of the primary connection but also improve the detection probability of the CR. Furthermore, in the case of missed detection, relaying diversity can protect the primary link from multi-access interference. It is worth noting that cooperative diversity is used in the cognitive literature as a part of the cognitive network in order to improve detection and resolve hidden-node problems [5]. In this letter cooperation is

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used as a part of the primary legacy network and introduces a new interplay between CR and cooperative diversity.

II. COGNITIVE RADIO AND COOPERATIVE DIVERSITY

A. System model and assumptions

The cognitive system is modeled as a basic four-node configuration consisting of one primary user P , one cognitive user S and the corresponding destinations (D_P , D_S) [2]. It is assumed that the primary link operates a legacy technology and thus the destination D_P (optimized for interference-free environments) can not deal with possible interference. On the other hand, the cognitive link can mitigate interference effects and thus the considered model corresponds to a Z -interference channel in the case of the primary system is not detected. A slow, flat, block Rayleigh fading environment is assumed, where the channel remains static for one coherence interval (one slot) and changes independently in different coherence intervals with a variance $\sigma_{i,j}^2 = d_{i,j}^{-\beta}$, where $d_{i,j}$ is the Euclidean distance between terminals i and j , and β is the path-loss exponent. Furthermore, additive white Gaussian noise is assumed with variance σ_n^2 .

For the investigated protocol, a relay node R is incorporated into the primary network in order to assist the primary source transmission. For simplicity, a full-duplex transmission mode is adopted, which allows the relay to transmit and receive simultaneously in two different frequency bands (\mathcal{W}_1 , \mathcal{W}_2) which are jointly bonded and allocated to the primary legacy network (i.e. compatible with LTE). Moreover, the total transmit power (P_0) in each transmission time slot remains the same and each terminal transmits with equal power. Perfect channel knowledge is assumed at the destinations but not at the transmitters and a Maximum-Ratio Combiner (MRC) is used at D_P . The radio sensing is based on a non-coherent energy detection in order to minimize the complexity of the system. It is worth noting that the frequency \mathcal{W}_2 is used as an intermediate frequency in order to implement the full-duplex constraint (diversity without extra resources) [6].

B. CR without cooperation

This case corresponds to a conventional deployment of the CR, where the cognitive link is added to the legacy network without further modifications. The considered non-coherent detection is based on the link $P \rightarrow S$, and the detection problem is described as follows:

$$\mathcal{H}_1 : y(k) = h_{P,S}x(k) + n(k), \quad (1)$$

$$\mathcal{H}_0 : y(k) = n(k), \quad (2)$$

$$T(y) = \frac{1}{K} \sum_{k=1}^K |y(k)|^2, \quad (3)$$

where hypotheses \mathcal{H}_1 and \mathcal{H}_0 denote the cases where the primary user is active and inactive, respectively, $h_{i,j}$ is the

block fading coefficient for the link $i \rightarrow j$ (for the slot under consideration), x is the transmitted signal with variance σ_x^2 , K is the number of samples for the spectrum sensing and T is the test statistic of the energy detector. The quality of the sensing detection is described by the probability of detection, P_d , and the probability of false alarm, P_f , which are defined as the probabilities that the sensing algorithm detects a primary user under hypotheses \mathcal{H}_1 and \mathcal{H}_0 , respectively. According to the central limit theorem (CLT), the test statistic T for each case can be approximated by Gaussian distributions with parameters

$$\mu_0 = \sigma_n^2, \quad \sigma_0^2 = \frac{\sigma_n^4}{K}, \quad (4)$$

$$\mu_1 = |h_{P,S}|^2 \sigma_x^2 + \sigma_n^2, \quad \sigma_1^2 = \frac{(|h_{P,S}|^2 \sigma_x^2 + \sigma_n^2)^2}{K}, \quad (5)$$

where μ_i and σ_i^2 denote the mean and the variance of the Gaussian distribution for the hypothesis \mathcal{H}_i . As $|h_{P,S}|^2$ is an exponential random variable with a parameter $\lambda = d_{P,D_P}^\beta$, the probabilities P_f and P_d can be written as

$$P_d = \Pr\left\{T(y) > \epsilon \mid \mathcal{H}_1\right\} = \frac{\lambda}{\sigma_x^2} e^{\frac{\lambda \sigma_x^2}{\sigma_n^2}} \int_{\sigma_n^2}^{\infty} Q\left(\sqrt{K} \left[\frac{\epsilon}{x} - 1\right]\right) e^{-\frac{\lambda x}{\sigma_x^2}} dx, \quad (6)$$

$$P_f = \Pr\left\{T(y) > \epsilon \mid \mathcal{H}_0\right\} = Q\left(\sqrt{K} \left[\frac{\epsilon}{\sigma_n^2} - 1\right]\right), \quad (7)$$

where ϵ is the energy threshold and $Q(t) = (1/\sqrt{2\pi}) \int_t^{\infty} e^{-t^2/2} dt$ is the Q -function. For a targeted false alarm probability, \overline{P}_f , the probability of the detection using the energy detector is given by substituting Eq. (7) into (6)

$$P_d = \frac{\lambda}{\sigma_x^2} e^{\frac{\lambda \sigma_x^2}{\sigma_n^2}} \int_{\sigma_n^2}^{\infty} Q\left(\frac{[Q^{-1}(\overline{P}_f) + \sqrt{K}] \sigma_n^2 - \sqrt{K}}{x}\right) e^{-\frac{\lambda x}{\sigma_x^2}} dx. \quad (8)$$

As the basic goal of the considered cognitive system is the performance of the primary user, the outage probability for the primary link can be written as

$$P_{out} = P_d \underbrace{\Pr\left\{\log(1 + P_0 |h_{P,D_P}|^2 / \sigma_n^2) < R_0\right\}}_{\triangleq \Psi_{P,D_P}(P_0)} + (1 - P_d) \Pr\left\{\log\left(1 + \frac{P_0 |h_{P,D_P}|^2}{P_0 |h_{S,D_P}|^2 + \sigma_n^2}\right) < R_0\right\}, \quad (9)$$

where R_0 is the required spectral efficiency. The above outage probabilities are well-known in the literature and can be found in [4], [7].

C. CR with cooperation via “dumb” and “cognitive” relays

According to Eq. (9), the basic reason for performance degradation of the legacy link is the missed detection of the primary user as well as the lack of protection against potential interference at the primary destination. In order to tackle both issues, the proposed scheme increases the sensing ability of the system and protects the primary destination from multi-access interference via cooperative diversity. More specifically, it is assumed that a DF relay node (R) is added to the

primary link in order to assist communication. In the case that this relay successfully decodes the transmitted primary signal, it provides a diversity gain which can be useful for both cognitive and primary perspectives. The cognitive user senses both frequency bands one by one with the sensing time to be reduced to half for each in order to satisfy the sensing time constraint ($K/2$ samples per band). The sensing results from the two bands are then combined to make the final sensing decision. Equivalent to Eq. (8), the expression between detection and false alarm probabilities for the spectrum \mathcal{W}_i can be written as

$$P_{d,i} = \xi_i \frac{\lambda_i}{\sigma_x^2} e^{\frac{\lambda_i \sigma_x^2}{\sigma_n^2}} \int_{\sigma_n^2}^{\infty} Q\left(\frac{[Q^{-1}(\overline{P}_{f,i}) + \sqrt{K/2}] \sigma_n^2 - \sqrt{K/2}}{x}\right) e^{-\frac{\lambda_i x}{\sigma_x^2}} dx + (1 - \xi_i) \overline{P}_{f,i}, \quad (10)$$

where $\overline{P}_{f,i}$ is the targeted false probability for the band \mathcal{W}_i , $\lambda_1 = 0.5d_{P,S}^\beta$, $\lambda_2 = 0.5d_{R,S}^\beta$, $\xi_1 \equiv 1$ and $\xi_2 = 1 - \Psi_{P,R}(P_0/2)$ denotes the probability that the relay can successfully decode the primary signal.

To make a final decision about the activity of the primary user, the cognitive user combines the sensing results from both frequency bands. In this work we consider an OR fusion rule where the cognitive user declares presence of the primary user when it detects the primary signal in either band [8]. By optimizing the threshold in each frequency band (dynamic optimization), the detection probability can be written as

$$P_d^{\text{OR}} = \max_{1 - \prod_{i=1}^2 (1 - \overline{P}_{f,i}) = \overline{P}_f} \left\{1 - (1 - P_{d,1})(1 - P_{d,2})\right\}. \quad (11)$$

The outage probability of the primary link introduces two versions of the cooperative protocol according to the intelligence of the relay node. Under a “dumb” scenario, the relay is also a node of the legacy network and therefore can not suppress possible interference. In the case of a missed detection, the relay decodes the primary signal without further processing which results in a poor diversity gain for the system. The outage performance of the primary link can be written as

$$P'_{out} = P_d^{\text{OR}} \underbrace{\left[\underbrace{\Psi_{P,R}(P_0/2) \Psi_{P,D_P}(P_0/2)}_{\text{non-diversity}} + \underbrace{(1 - \Psi_{P,R}(P_0/2)) P_1}_{\text{diversity}} \right]}_{\text{detection}} + (1 - P_d^{\text{OR}}) \underbrace{\left[\underbrace{\zeta P_2}_{\text{non-diversity}} + \underbrace{(1 - \zeta) P_3}_{\text{diversity}} \right]}_{\text{missed detection}}, \quad (12)$$

where $\zeta = \Pr\{\log(1 + P_0 |h_{P,R}|^2 / [2P_0 |h_{S,R}|^2 + 2\sigma_n^2]) < R_0\}$, $P_1 = \Pr\{\log(1 + [P_0 |h_{P,D_P}|^2 + P_0 |h_{R,D_P}|^2] / 2\sigma_n^2) < R_0\}$, $P_2 = \Pr\{\log(1 + P_0 |h_{P,D_P}|^2 / [2P_0 |h_{S,D_P}|^2 + 2\sigma_n^2]) < R_0\}$ and $P_3 = \Pr\{\log(1 + [P_0 |h_{P,D_P}|^2 + P_0 |h_{R,D_P}|^2] / [2P_0 |h_{S,D_P}|^2 + 2\sigma_n^2]) < R_0\}$ (the analytical expressions are not given here due to the space limitations-see [3], [4]).

The bottleneck from the above “dumb” behavior of the relay, motivates our proposal of a cognitive relay. In this scenario, the relay node has some intelligence and can suppress

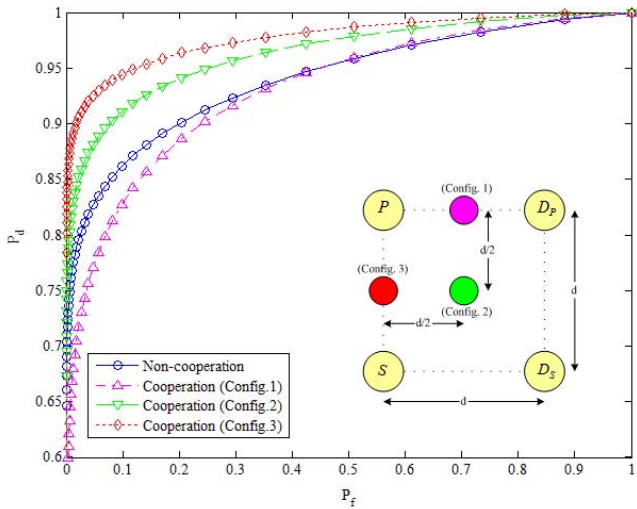


Fig. 1. Probability P_d versus P_f for different relay configurations; $\sigma_x^2/\sigma_n^2 = 40$ dB, $K = 100$ samples, $\beta = 2$, $d = 100$ unit length.

(i.e. via interference cancellation [3]) possible multi-access interference. Although the sensing ability of the system remains similar to the above case, the consideration of cognitive relays provides a more reliable diversity gain and modifies the outage performance of the primary link by replacing probability ζ in Eq. (12) with $\zeta' = \Pr\{\log(1 + P_0|h_{P,R}|^2/2\sigma_n^2) < R_0\}$.

III. NUMERICAL RESULTS

The simulation environment follows the model of Section II and consists of a 2D square topology where the nodes are located according to Fig. 1. The path-loss exponent is set to $\beta = 2$ and the dimension of the network is 100×100 unit lengths. The transmit signal is assumed to be an i.i.d Gaussian random process. The sensing time for cognitive user is $K = 100$ samples. Fig. 1 plots the P_d versus the P_f for the non-cooperative and the proposed cooperative scheme and for three indicative relay locations. The transmitted power is equal to $P_0 = 40$ dB which corresponds to poor direct links. As can be seen, the proposed method outperforms the non-cooperative case for the configurations 2 and 3. Cooperative diversity improves the reliability of the $P \rightarrow S$ link and provides more opportunities to the secondary user to sense the radio. However, the location of the relay is a critical parameter for the cooperative sensing performance. The location of the relay closer to the secondary user (config. 3) improves the detection performance by offering a higher diversity gain. On the other hand, when the relay is located far from the secondary user (config. 1), the detection performance becomes worse than the one of non-cooperative scheme. According to the power constraint, in the cooperative mode, the primary user transmits half of the maximum power which yields a sensing degradation when diversity gain is not available at the secondary user.

Fig. 2 shows the impact of the relay behavior on the outage performance of the primary link. The location of the relay follows the above described configuration 2, the detection probability is equal to $P_d = 0.9$ and the required spectral efficiency is $R_0 = 0.1$ bits per channel per use (BPCU). The non-CR scenario as well as the case CR without cooperation

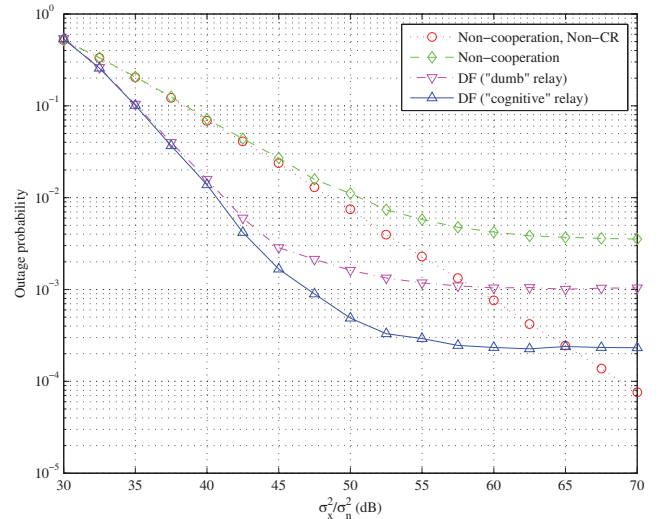


Fig. 2. Outage probability versus transmitted SNR for the primary link via "dumb" and "cognitive" cooperation; Config. 2, $P_d = 0.9$, $R_0 = 0.1$ BPCU.

are used as reference curves. The first important observation is that the proposed cooperative scheme outperforms the conventional CR at high signal-to-noise ratios (SNRs) for both cases ("dumb" and "cognitive"). The related diversity gain protects the primary link from interference and thus provides a better outage performance. Furthermore, as can be seen, the "cognitive" relay strategy outperforms the "dumb" strategy and offers a higher performance for high SNRs. The mitigation of the interference by the "cognitive" relay provides more diversity opportunities to the system and thus protects more efficiently the primary link from interference.

IV. CONCLUSION

This letter has investigated a low-cost solution for providing CR benefits to inflexible legacy networks. We have shown that the enhancement of the primary link with cooperative diversity improves the sensing ability of the cognitive system while protecting the primary connection from possible interference under a missed detection. The proposed approach seems to be an efficient solution for practical applications as its implementation does not require complex network modifications or expensive infrastructure updates.

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