Energy Efficient Ultra-Wideband Signaling for Cooperative Spectrum Sensing in Cognitive Radio

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***Abstract*—The reliable detection of unused spectrum while meeting a required probability of detecting primary user activity is a key functionality of cognitive radio systems. In cooperative spectrum sensing, the detection results of multiple cognitive radios are combined to a global result with high reliability. In order to transmit the local decisions a signaling channel is required. It can be realized by ultra-wideband underlay communications in parallel to primary user activity. Due to strict limitations on the transmission power for ultra-wideband communications, it is crucial to carefully allocate power levels to minimize channel errors, which could corrupt the transmission of local decisions. In this paper, an approach for the allocation of transmission power levels for the signaling channel is proposed, which aims to maximize the global probability of detecting spectrum holes while detecting primary user activity with a given reliability. Numerical results based on real spectrum measurements show the feasibility and illustrate the performance of the approach.**

I. Introduction

Cognitive radio promises to significantly increase spectral efficiency by allowing secondary users to temporarily utilize unused parts of the spectrum of licensed primary users (PUs) [1]. Cognitive radios (CRs) are capable of monitoring the spectrum domain with the goal to detect spectrum holes which can be used for radio transmissions without interfering with the PU. The reliability of spectrum sensing can be significantly improved by introducing a cooperative sensing approach where the final detection result is based on the combination of local decisions collected from various distributed CRs [2]. In a cooperative network of CR users, a central unit like a base station or an access point combines the local decisions of the CRs and reliably decides whether the spectrum is occupied or not.

One of the challenging tasks in the design of cooperative spectrum sensing is the implementation of the signaling channel, which is, e.g., required to transmit the local decisions to the base station. It can be realized by an underlay system, e.g., based on ultra-wideband (UWB) technology which operates with an ultra low power spectral density and can therefore be used in parallel to licensed radio systems [3]. The implementation in an underlay manner provides the attractive possibility to immediately exchange local detection results of the CRs even when the spectrum of interest is occupied by the primary user [4]. Since regulatory bodies have imposed strict power limits for the usage of ultra-wideband signals, the transmission of the local detection results is subject to channel errors caused by noise and interference. Yet, the channel quality can be controlled by appropriate assignment of transmission power levels. In this paper, we propose an application-specific approach for the assignment of transmission power levels for the ultra-wideband signaling channel of a cooperative spectrum sensing system. It aims to maximize the detection performance given a total power constraint for the signaling channel. To validate this approach, we employ real spectrum sensing results obtained in a typical office environment. Numerical results show a significant gain in terms of an increased global probability of detecting spectrum holes compared to uniform power assignment especially for the practically important case of strict power limitations for the signaling channel.

The remainder of the paper is organized as follows. Section II introduces the system model for cooperative spectrum sensing and in Section III the model for the UWB signaling channel is stated. The proposed power allocation procedure for the signaling channel is presented in Section IV. Finally, in Section V the setup for practical spectrum sensing is described and numerical results are presented.

II. Cooperative Spectrum Sensing

The problem of cooperative spectrum sensing can formally be modelled as follows. We consider a binary hypothesis testing problem with hypotheses H_0 and H_1 indicating whether the spectrum is occupied (H_0) or free (H_1). In order to detect the presence of a spectrum hole, a network of N CRs obtains random observations

$$(X_1, \dots, X_N)' \in \mathcal{X}_1 \times \cdots \times \mathcal{X}_N, \tag{1}$$

which are generated according to either H_0 or H_1. The random observations $X_1, \dots, X_N$ are assumed to be conditionally independent given the underlying hypothesis, yet they do not have to be identically distributed. According to the distributed nature of the problem, the jth CR performs independent spectrum sensing and processes its respective observation X_j by forming a local decision $U_j = \delta_j(X_j)$ about the absence or presence of a spectrum hole.

A. CR decision rules

In the case of hard local decisions, the CR decision rules δ_j are mappings

$$\delta_j \colon \mathcal{X}_j \to \{0, 1\}, \quad j = 1, \dots, N. \tag{2}$$

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As is known from the distributed detection literature [5], local decision rules leading to jointly optimal configurations are monotone likelihood ratio tests. In this way, each CR can be assigned a local probability of false alarm according to

$$P_{f_j} = P(U_j = 1|H_0) = P(L_j > \tau_j|H_0) \tag{3}$$

and a local probability of detection according to

$$P_{d_j} = P(U_j = 1|H_1) = P(L_j > \tau_j|H_1), \tag{4}$$

where $L_j = \log(f_j(X_j|H_1)/f_j(X_j|H_0))$ is the local log-likelihood ratio of observation X_j. The local probability of miss $P_{m_j} = P(U_j = 0|H_1)$ is given by $P_{m_j} = 1 - P_{d_j}$.

The local decision threshold τ_j might be chosen to maximize the Kullback-Leibler (KL) distance between the local detection probabilities [6].

B. Transmission of local decisions

Upon local spectrum sensing, the CRs transmit the preliminary decisions $U_1, \dots, U_N$ to the base station of the CR system for decision combining. Due to noisy signaling channels, the received decisions $\widetilde{U}_1, \dots, \widetilde{U}_N$ are potentially corrupted. We model the signaling channel of the jth CR by a binary symmetric channel with bit-error probability ε_j, i.e.

$$\varepsilon_j = P(\widetilde{U}_j = 1|U_j = 0) = P(\widetilde{U}_j = 0|U_j = 1). \tag{5}$$

The modified probabilities $\widetilde{P}_{f_j} = P(\widetilde{U}_j = 1|H_0)$, $\widetilde{P}_{d_j} = P(\widetilde{U}_j = 1|H_1)$ and $\widetilde{P}_{m_j} = P(\widetilde{U}_j = 0|H_1)$ can be calculated as

$$\begin{aligned} \widetilde{P}_{f_j} &= P_{f_j} + \varepsilon_j(1 - 2P_{f_j}), \\ \widetilde{P}_{d_j} &= P_{d_j} + \varepsilon_j(1 - 2P_{d_j}), \\ \widetilde{P}_{m_j} &= P_{m_j} + \varepsilon_j(1 - 2P_{m_j}). \end{aligned} \tag{6}$$

C. Fusion of local decisions

Under the assumption of conditionally independent local decisions $U_1, \dots, U_N$ at the CRs and independent binary symmetric channels, the optimal fusion rule at the CR base station under the Neyman-Pearson criterion can be implemented by a linear threshold test [7]

$$\sum_{j=1}^{N} \widetilde{\lambda}_j \widetilde{U}_j \underset{U_0 = 0}{\overset{U_0 = 1}{\gtrless}} \vartheta \tag{7}$$

with weights

$$\widetilde{\lambda}_j = \log\left(\frac{\widetilde{P}_{d_j}(1 - \widetilde{P}_{f_j})}{\widetilde{P}_{f_j}(1 - \widetilde{P}_{d_j})}\right) \tag{8}$$

for $j = 1, \dots, N$, and a decision threshold $\vartheta = \vartheta(\alpha)$, where α is the maximum acceptable global probability of false alarm P_F. The tie-breaking in the decision rule is done in a randomized way such that the whole confidence level α is exploited [6]. The global decision U_0 is characterized by the global probability of detection $P_D = P(U_0 = 1|H_1)$ and the global probability of false alarm $P_F = P(U_0 = 1|H_0)$.

III. IR-UWB Signaling Channel

Since ultra-wideband communications can be used in an underlay manner in parallel to the PU, it is perfectly suited as signaling channel for cognitive radio systems. We consider IR-UWB with pulse position modulation with modulation index ξ and pseudorandom time hopping codes as multiple access scheme as described in [8]. The transmitted signal from the jth CR can then be written as

$$s_j(t) = A_j \sum_{i=-\infty}^{\infty} w(t - iT_f - c_i^{(j)} T_c - \xi d^{(j)}_{\lfloor i/N_j \rfloor}), \tag{9}$$

where T_f denotes the length of a time frame in which one impulse of form $w(t)$ is transmitted. In the frame, the impulse is delayed by an integer multiple of the chip length T_c according to the time hopping code $c_i^{(j)}$. Each data bit $d^{(j)}$ corresponding to the local decision U_j of the jth CR is transmitted by a number of N_j equally modulated pulses with amplitude A_j.

A. Signal-to-interference-and-noise ratio

In a multi-user scenario the SINR γ_j of the jth CR can be written as [9]

$$\gamma_j = N_j \frac{g_j p_j}{\sigma^2 \sum_{k \neq j} g_k p_k + \frac{1}{T_f}\eta}, \tag{10}$$

with p_j denoting the transmission power for the signaling channel of the jth CR. The parameter σ^2 depends on the correlation properties of the employed pulse form $w(t)$. The path gain between the jth CR and the CR base station is denoted by g_j. The transmitted signal is subject to additive white Gaussian noise with energy η. Using the standard Gaussian approximation for multiple access interference, the bit error rate ε_j of the jth CR can be expressed as

$$\varepsilon_j = \tfrac{1}{2}\mathrm{erfc}(\sqrt{\gamma_j}). \tag{11}$$

B. Power assignment

A power allocation that jointly meets given target-SINRs $\gamma_1^T, \dots, \gamma_N^T$ with minimum total transmission power can be obtained using a special case of the dimensionality reduction procedure presented in [9]. If a feasible solution exists, the power of the jth CR can be computed very efficiently by

$$p_j = \frac{\frac{\eta}{T_f \sigma^2}}{g_j \left(\frac{N_j}{\sigma^2 \gamma_j^T} + 1\right)\left(1 - \sum_{k=1}^{N} \frac{1}{\frac{N_k}{\sigma^2 \gamma_k^T} + 1}\right)}. \tag{12}$$

IV. Optimal Power Allocation for the Signaling Channel

To optimize system performance we aim to maximize the global probability of detecting spectrum holes P_D given a total transmission power p_{tot} for the signaling channel of all CRs. The restriction α on the global probability of false alarm P_F is met by an appropriate choice of $\vartheta(\alpha)$ as discussed in Section II. Unfortunately, there is no closed form expression for the global probability of detection P_D. Hence, it is infeasible to directly solve the problem.

Therefore, we consider a closely related problem, which is derived from the optimal channel-aware fusion rule (7). In this rule, the global decision U_0 is based on the weighted sum of the received decisions, with weights $\widetilde{\lambda}_j$ given by (8). These weights can be interpreted as a measure for the local detection performance of a CR, that also includes the quality of the signaling channel. The weight $\widetilde{\lambda}_j$ increases with increasing P_{d_j} and decreasing P_{f_j} and it decreases with an increasing BER ε_j of the signaling channel. To optimize the global detection performance, we therefore aim to maximize the sum of all effective weights given the total transmission power p_{tot}, i.e.

$$\underset{p_1,\ldots,p_N}{\text{maximize}} \; \sum_{j=1}^{N} \widetilde{\lambda}_j \tag{13}$$

$$\text{subject to} \; \sum_{j=1}^{N} p_j \leq p_{\text{tot}} \tag{14}$$

$$p_j \geq 0, \; j = 1, \ldots, N. \tag{15}$$

We first restrict ourselves to the simpler case with completely orthogonal channels.

A. Power control in case of orthogonal channels

Orthogonal signaling channels between the CRs and the CR base station result in a decoupled objective function in the sense that changing the transmission power p_j of the jth CR only has an influence on the effective weight $\widetilde{\lambda}_j$ of this CR. Therefore it holds that

$$\frac{\partial}{\partial p_j} \sum_{k=1}^{N} \widetilde{\lambda}_k = \frac{\partial}{\partial p_j} \widetilde{\lambda}_j. \tag{16}$$

The first derivative of the objective function with respect to the transmission power p_j of the jth CR is given by

$$\begin{aligned} \frac{\partial}{\partial p_j} \widetilde{\lambda}_j = & \frac{a(2P_{f_j} - 1)}{\widetilde{P}_{f_j} - 1} - \frac{a(2P_{f_j} - 1)}{\widetilde{P}_{f_j}} \\ & + \frac{a(2P_{m_j} - 1)}{\widetilde{P}_{m_j} - 1} - \frac{a(2P_{m_j} - 1)}{\widetilde{P}_{m_j}} \end{aligned} \tag{17}$$

with

$$a = \frac{\sqrt{N_j T_f g_j} \exp(-\frac{N_j T_f g_j p_j}{\eta})}{2\sqrt{\pi p_j \eta}} \tag{18}$$

For orthogonal communication channels, the effective weight $\widetilde{\lambda}_j$ according to (8) is strictly monotonically increasing in the transmission power $p_j > 0$ since all terms in (17) are greater than zero and hence $\partial \widetilde{\lambda}_j / \partial p_j > 0$ for $p_j > 0$. Due to strict positive monotonicity, an increased transmission power always results in an increase of the objective function. Hence, the optimal power allocation is always attained at the boundary $p_{\text{tot}} = \sum_j p_j$.

Let

$$\mathcal{S}_j = \{(P_{f_j}, P_{m_j}) : \frac{\partial^2}{\partial p_j^2} \widetilde{\lambda}_j < 0, \; p_j \geq 0\} \tag{19}$$

denote the set of local error probabilities, for which the second derivative of $\widetilde{\lambda}_j$ with respect to p_j is negative for all power levels $p_j \geq 0$. Numerical evaluation shows that for arbitrary combinations of P_{f_j} and P_{m_j} the second derivative is negative for all power levels p_j of practical interest (evaluated from 0 W up to a transmission power of 3 W per node)

Restricting to region $\mathcal{S}_j$, the effective sensor weight is concave in p_j and there exists a unique maximum which due to strict monotonicity is attained at the boundary $p_{\text{tot}} = \sum_j p_j$. For region $\mathcal{S}_j$, we have a concave objective function and a convex set of constraints. This implies that Karush-Kuhn-Tucker (KKT) theory can be used to characterize the optimal power allocation $\boldsymbol{p}$. The Lagrangian L for the problem is given by [10]

$$L = \sum_{j=1}^{N} \widetilde{\lambda}_j - \varrho(\sum_{j=1}^{N} p_j - p_{\text{tot}}) + \sum_{j=1}^{N} \nu_j p_j \tag{20}$$

where ϱ and ν_j are Lagrange multipliers. The optimality conditions are

$$\frac{\partial}{\partial p_j} \sum_{k=1}^{N} \widetilde{\lambda}_k - \varrho + \nu_j = 0, \quad j = 1, \ldots, N, \tag{21}$$

$$\sum_{j=1}^{N} p_j - p_{\text{tot}} = 0, \tag{22}$$

$$\nu_j p_j = 0, \quad j = 1, \ldots, N, \tag{23}$$

$$p_j \geq 0, \quad j = 1, \ldots, N, \tag{24}$$

$$\nu_j \geq 0, \quad j = 1, \ldots, N. \tag{25}$$

From conditions (23) – (25) it can be concluded that ν_j has to be equal to zero if $p_j > 0$. For a given ϱ, we then have to solve

$$\frac{\partial}{\partial p_j} \sum_{k=1}^{N} \widetilde{\lambda}_k - \varrho = \frac{\partial}{\partial p_j} \widetilde{\lambda}_j - \varrho = 0 \tag{26}$$

with respect to p_j to obtain the optimal transmission power of the jth CR. For $p_j > 0$ the derivative $\partial \widetilde{\lambda}_j / \partial p_j$ of all CRs has to be equal to ϱ. The parameter ϱ is chosen such that constraint (22) is met.

B. Power control in case of non-orthogonal channels

IR-UWB systems with pseudorandom time hopping operate over non-orthogonal channels. The power control procedure in case of orthogonal channels is mainly based on the fact that the objective function is decoupled according to (16). In case of non-orthogonal channels however, the objective function is not decoupled, because increasing the power of one CR has an impact on the effective weight of all other CRs due to interference. To attain a decoupled objective function also in the case of non-orthogonal channels, we do not directly

Algorithm 1 Power control in case of non-orthogonal channels

```
for j = 1 : N do
    γ_j ← N_j (g_j p_tot/N) / (σ² Σ_{k≠j} g_k p_tot/N + (1/T_f) η);
end for
γ_min ← min_j γ_j;
ϱ_min ← 0;
ϱ_max ← max_j ∂/∂γ_j λ̃_j(γ_min · g_min/g_max);
p'_tot ← 0;
while |p_tot − p'_tot| > μ do
    for j = 1 : N do
        γ_j^T ← (g_j/g_min) · (∂/∂γ_j λ̃_j)^{-1} (½(ϱ_max − ϱ_min) + ϱ_min);
    end for
    for j = 1 : N do
        p_j ← (η/(T_f σ²)) / ( g_j (N_j/(σ² γ_j^T) + 1) (1 − Σ_{i=1}^{N} 1/(N_i/(σ² γ_i^T) + 1)) );
    end for
    p'_tot ← Σ_{j=1}^{N} p_j;
    if |p_tot − p'_tot| ≤ μ then
        return p;
    else
        if p'_tot > p_tot then
            ϱ_min ← ½(ϱ_max − ϱ_min) + ϱ_min;
        end if
        if p'_tot < p_tot then
            ϱ_max ← ½(ϱ_max − ϱ_min) + ϱ_min;
        end if
    end if
end while
```

determine the transmission power allocation, but target-SINRs for all nodes. Varying the SINR of one node does not influence the SINR of other nodes if the transmission power levels of all nodes are properly adjusted. The transmission power to jointly meet the target-SINRs for all CRs is given by (12). To find a good power allocation for the case of non-orthogonal channels, we use a similar approach as used for the case of orthogonal channels.

At the optimal solution in case of orthogonal channels the derivative of the effective weight with respect to the power is equal for all CRs. Since we can decouple the objective function in case of non-orthogonal channels by considering SINR instead of power we consider an SINR allocation for which all derivatives of the effective weights with respect to the SINR is equal for all CRs, i.e.

$$\frac{\partial}{\partial \gamma_j} \sum_{k=1}^{N} \widetilde{\lambda}_k = \frac{\partial}{\partial \gamma_j} \widetilde{\lambda}_j = \varrho. \tag{27}$$

To account for signal attenuation in the SINR assignment we also consider fading conditions. Usually a higher transmission power is necessary to meet a target-SINR for nodes that have low path gain compared to CRs with high path gain. To consider this fact we additionally use a weighting factor given by the path gain g_j of the jth CR to the CR base station normalized by the minimum path gain g_{min} of a CR in the network. Eventually, we determine the target-SINR γ_j according to

$$\gamma_j^T = \left(\frac{g_j}{g_{\text{min}}}\right) \cdot \left(\frac{\partial \widetilde{\lambda}_j}{\partial \gamma_j}\right)^{-1} (\varrho). \tag{28}$$

This is a similar strategy as presented in [11]. The parameter ϱ has to be chosen such that the total power constraint is met. This can be accomplished as explained in the following.

The parameter ϱ takes on values in a finite interval. If we allocate the full total transmission power p_{tot}, not all target-SINRs can be arbitrarily small. As ϱ is monotonically decreasing with $\sum_j p_j$, we obtain an upper bound $\varrho_{\max}$ for ϱ by choosing an SINR allocation that results in $\sum_j p_j < p_{\text{tot}}$. This bound is given by the maximum value of the derivative $\frac{\partial}{\partial \gamma_j} \widetilde{\lambda}_j$ of all nodes evaluated at the minimum SINR γ_{min} that would result from uniform power allocation $p_j = p_{\text{tot}}/N$ multiplied by $g_{\text{min}}/g_{\text{max}}$ to account for the weighting factor. Due to strict monotonicity of $\widetilde{\lambda}$ in γ, a lower bound for the minimum value of ϱ is given by zero. This implies that ϱ has to be in the interval $[0, \max_j \frac{\partial}{\partial \gamma_j} \widetilde{\lambda}_j(\gamma_{\text{min}} \cdot (g_{\text{min}}/g_{\text{max}}))]$. We can use a bi-section strategy to find the optimal ϱ that fulfills the total power constraint up to a predefined accuracy μ. The complete algorithm for the case of non-orthogonal channels that returns the power allocation $\boldsymbol{p}$ is given in Algorithm 1.

TABLE I
OBSERVATION SNR AND DISTANCE TO THE CR BASE STATION OF DIFFERENT MEASUREMENT POINTS

Point	SNR [dB]	d_j [m]
1	−4.05	15.2
2	−9.90	15.8
3	−4.76	8.7
4	2.81	7.7
5	0.40	4.5
6	0.16	9.2
7	3.95	7.5
8	6.28	4.9
9	6.56	2.2
10	7.49	7.9
11	8.84	5.1
12	9.40	4.6
13	8.69	3.2
14	5.46	13.2
15	8.03	10.3
16	9.38	9.8

V. NUMERICAL RESULTS

To evaluate the validity of the proposed approach for the case of non-orthogonal channels in practice, we have employed software defined radios to sense the spectrum of an WiMAX-like OFDM signal as PU in an indoor office environment. Each of the CRs, experiencing different signal attenuations, observes the absence or presence of the OFDM signal in a 5 MHz wide frequency range. The spectrum sensing

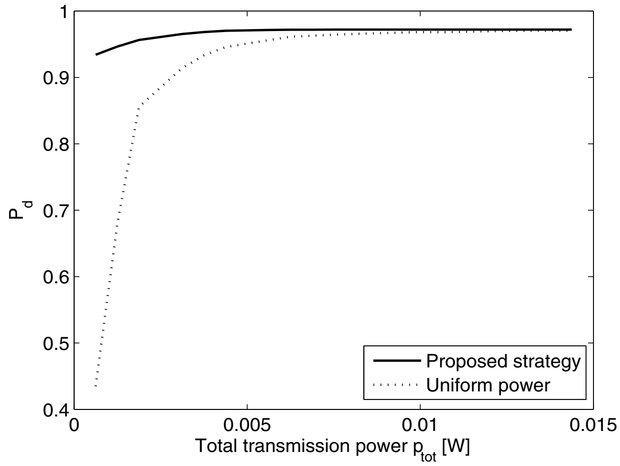

Fig. 3. Global probability of detection P_D as a function of the total transmission power p_{tot} for the proposed power assignment strategy compared to uniform power allocation.

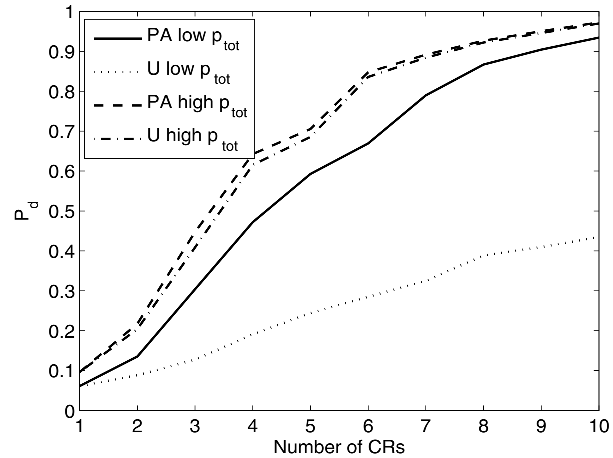

Fig. 4. Global probability of detection P_D as a function of the number of cognitive radios for different values of total transmission power p_{tot} for the proposed strategy compared to uniform power allocation.

TABLE II
PARAMETERS USED IN THE SIMULATION

parameter	value
β	2
σ^2	$1.9966 \cdot 10^{-3}$
N_j	10
T_c	2 ns
T_f	100 ns
η	10^{-11} J

is based on energy detection. The achieved observation SNRs and the distances d_j to the CR base station of the different measurement points are summarized in Table I. More details to the spectrum measurements can be found in [6]. The spectrum measurement results are combined with simulation data for the UWB signaling channel. For the transmission, we consider path gain according to $d^{-\beta}$. The simulation parameters are summarized in Table II.

Fig. 3 shows the global probability of detecting unused spectrum P_D as a function of the total transmission power p_{tot} for 10 CRs for the proposed power assignment strategy and for a uniform power allocation. The value of P_D is obtained by averaging the detection results of 100 different randomly chosen subsets of the measurement points in Table I. The global probability of false alarm P_F is restricted by $P_F \leq \alpha = 0.05$. It can be observed that the proposed strategy performs significantly better in case of the practically important case of low p_{tot}. The corresponding gain for low p_{tot} is greater than $100\,\%$. Fig. 4 shows the global probability of detecting spectrum holes depending on the number of CRs for uniform power assignment (U) and the power-aware approach (PA) for high and low p_{tot}. Of course, for all strategies the probability P_D increases with N. However, especially for low p_{tot} the slope of the curve is much higher for the proposed approach resulting in the large performance gain as observed in Fig. 3. For high p_{tot} the gain decreases due to quasi error free transmission in both strategies.

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