Handbook of Research on Software-Defined and Cognitive Radio Technologies for Dynamic Spectrum Management

Naima Kaabouch  
*University of North Dakota, USA*

Wen-Chen Hu  
*University of North Dakota, USA*
Chapter 4

Energy-Efficient Cooperative Spectrum Sensing for Cognitive Radio Networks

Saud Althunibat
University of Trento, Italy

Sandeep Narayanan
WEST Aquila s.r.l., Italy & University of L'Aquila, Italy

Marco Di Renzo
Laboratory of Signals and Systems (L2S), France

Fabrizio Granelli
University of Trento, Italy

ABSTRACT

One of the main problems of Cooperative Spectrum Sensing (CSS) in cognitive radio networks is the high energy consumption. Energy is consumed while sensing the spectrum and reporting the results to the fusion centre. In this chapter, a novel partial CSS is proposed. The main concern is to reduce the energy consumption by limiting the number of participating users in CSS. Particularly, each user individually makes the participation decision. The energy consumption in a CSS round is expected by the user itself and compared to a predefined threshold. The corresponding user will participate only if the expected amount of energy consumed is less than the participation threshold. The chapter includes optimizing the participation threshold for energy efficiency maximization. The simulation results show a significant reduction in the energy consumed compared to the conventional CSS approach.

1. INTRODUCTION

Recently, energy efficiency in wireless networks has received a significant amount of research. This is because mobile users are usually battery-powered. The limited energy resources represent a challenge hindering wide implementation of some recent technologies (Fettweis & Zimmermann, 2008). Some wireless systems, such as cognitive radio (CR), implies more energy consumption than other systems. Cognitive radios in general require more energy to operate, as compared to the conventional transceivers due to the additional tasks required to perform cognitive transmission. In CR, a licensed spectrum can be exploited by unlicensed users when it is (temporarily and spatially) unused by licensed users. This requires awareness of spectrum status, which is performed by a process termed as spectrum sensing (Mitola & Maguire, 1999), (Haykin, 2005).

DOI: 10.4018/978-1-4666-6571-2.ch004
In order to identify the unused spectrum portions, the unlicensed users, also called cognitive users (CUs), are enforced to sense it for specific period, inducing energy consumption which does not exist in the typical wireless systems. Moreover, aiming at improving the reliability of spectrum sensing, cooperative spectrum sensing (CSS) is proposed (Mishra, Sahai & Brodersen, 2006), (Di Renzo, Imbriligo, Graziosi & Santucci, 2009), (Ghasemi & Sousa, 2007). In CSS, the local sensing results are reported to a central entity, called fusion centre (FC). The FC is in charge of making a global decision regarding the spectrum occupancy by applying a specific fusion rule (FR). Although CSS decreases the probability of erroneous decision considerably by mitigating the effects of multipath fading and shadowing, it causes extra delay, security risks (I.F. Akyildiz, Lo & Balakrishnan, 2011) (Di Renzo Graziosi & Santucci, April 2009) and more energy consumption.

The high energy expenditure in CSS is caused by the individual sensing and reporting the sensing results to the FC. In case of large number of CUs and/or large number of sensed channels, energy-efficient CSS becomes a pressing need for CR systems. Aiming at reducing energy consumption, limiting the amount of reported results has been widely investigated. In general, two well-known schemes for results’ reporting (S. Chaudhari, Lunden, Koivunen & Poor, 2012) (Viswanathan & Varshney, 1997), soft scheme (SS) and hard scheme(HS). In SS, the sensing result of each CU is quantized locally by a multiple number of bits and sent to the FC. On the other hand, the result is quantized by only one bit in HS. As a CU employing HS reports only one bit, it is clear that the energy consumption is lower than if SS is employed (Maleki, Chepuri, & Leus, 2011). Thus, in this work, we consider only HS.

Many works have investigated the reduction of energy consumption in CSS. These works can be classified into four different approaches: (i) Reducing the number of sensing users, (ii) Reducing the sensing time, (iii) Reducing the reported sensing data, and (ii) Optimizing the decision-making rule.

In the first approach, (Maleki et al., 2011), and (Pham, Zhang, Engelstad, Skeie & Eliassen, 2010) have proposed algorithms that use the minimum number of sensing users based on different setups while satisfying predefined thresholds on the detection accuracy. In (Cheng et al.,2012), the CUs are divided into non-disjoint subsets such that only one subset senses the spectrum while the other subsets enter a low power mode. The energy minimization problem is formulated as a network lifetime maximization problem with constraints the detection accuracy. An algorithm for user selection is proposed in (Najimi et. al., 2013), where the user subset that has the lowest cost function and guarantees the desired detection accuracy is selected. The cost function is related to the system energy consumption.

The works in (Zhao et al., 2012), (Feng et al., 2012) and (Pham, Zhang, Engelstad, Skeie & Eliassen, 2010) consider the sensing time as a possible approach to reduce the energy consumption. In (Zhao et al., 2012), the CUs perform an initial sensing stage and report their local decisions to the FC. If a global decision cannot be made (no majority exists), a longer sensing stage is used. In (Feng et al., 2012), a utility function that consists of the difference between the achievable throughput (revenue) and the consumed energy (cost) is maximized by optimizing the sensing time with a constraint on the detection probability. The optimal sensing time that maximizes the energy efficiency with constraints based on the detection accuracy is obtained in (Pham, Zhang, Engelstad, Skeie & Eliassen, 2010). A joint optimization of the number of sensing users, the sensing time and the local detection threshold is presented in (Gao et al., 2013), aiming to maximize the energy efficiency by imposing a constraint on the detection accuracy.

Following the third approach, censoring, confidence voting and clustering have been proposed. Censoring is a promising technique that can significantly reduce the reporting CUs. In censoring, a CU does not report its sensing result unless it lies outside a specific range (Sun et al., March 2007), (Lunden et al.,
Energy-Efficient Cooperative Spectrum Sensing for Cognitive Radio Networks

2007), (Appadwedula et al., 2008). The censoring thresholds are optimized for minimizing the energy consumption with constraints on the detection accuracy (Maleki et al., 2011). In (Maleki et al., 2013), truncated sequential sensing and censoring are combined in order to reduce the energy consumption in CSS. Specifically, the spectrum is sequentially sensed, and once the accumulated energy of the sensed samples lies outside a certain region, the sensing is stopped and a binary decision is sent to the FC. If the sequential sensing process continues until a timeout, censoring is applied and no decision is sent. The thresholds of the censoring region are optimized in order to minimize the maximum energy consumption per CU subject to a constraint on the detection accuracy. In (Lee et al., 2008), a confidence voting scheme is presented. It works as follows: if the spectrum sensing of a specific CU agrees with the global decision, it gains its confidence; otherwise, it loses its confidence. When a user’s confidence level drops below a threshold, it considers itself as unreliable and stops sending its results. But it still keeps sensing the spectrum and tracking the global decision. As long as the result matches, it gains its confidence. Once its confidence level passes beyond the threshold, it rejoins the voting. The energy saving and the detection accuracy of this approach are investigated in (Lee et al., 2008).

Clustering is a popular approach to reduce the overhead load between the CUs and the FC. In clustering, CUs are separated into clusters and one from each cluster is nominated as cluster-head, which is in charge of collecting sensing results from cluster-members and reporting a cluster-decision to the FC on behalf of the cluster-members (Sun et al., June 2007). The cluster-head is changed randomly in each CSS round. The energy saving and the accuracy loss are investigated in (Lee et al., 2008). In addition to energy consumption analysis, time delay is conducted in (Xia et al., 2009). In (Wei et al., 2010) and (Khasawneh et al., 2012) clustering and censoring approaches are combined in one energy-efficient algorithm considering the noisy reporting channels.

Another simple algorithm for reducing the number of reporting CUs without affecting the detection accuracy can be found in (Althunibat & Granelli, 2013 June). The idea is based on an instantaneous processing of the received results at the FC. Whenever a global decision can be made, the reporting process is terminated and the rest of the CUs do not report their local sensing results. Despite its simplicity, this approach does not impact the detection accuracy and it offers a higher energy efficiency than other algorithms.

Following the approach of optimizing decision-making rule, in (Peh et al., 2011), the fusion threshold of the K-out-of-N rule is optimized for maximizing energy efficiency without constraints, while a constraint on resulting interference represented by the missed detection probability is set in (Althunibat et al., 2013 December). In (Maleki et al., 2012), the optimal fusion threshold that maximizes the throughput of CRN is obtained with constraints on the consumed energy per CU and the overall detection probability.

In this chapter, a novel proposal for improving energy efficiency in CSS is presented. The proposed algorithm is based on limiting the number of participating CUs in CSS. However, the selection of the participating CUs is not random. Instead, those CUs that consume higher energy are prevented from participation in CSS. The participation decision of each CU is taken individually by the CU itself. In detail, each CU estimates the expected amount of energy that will be consumed if it participates, and compares it to a predefined threshold, called participation threshold. Accordingly, the CU will participate only if its expected energy consumption is less than the participation threshold. Using this approach, the users that will greatly increase the energy consumption will be prevented from participating, resulting in lower energy consumption. It is worth mentioning that the proposed approach improves the energy efficiency not only by reducing energy consumption but also by increasing the amount of successfully
transmitted data. The increase in amount of successfully transmitted data is due to the decrease in the overall false alarm probability, as the number of involving users in CSS decreases. As the number of the involving CUs depends on the predefined threshold, an optimization of this threshold is carried out to maximize energy efficiency.

The rest of this chapter is organized as follows; system model is described in Section II, where in-detail discussion of energy consumption during CSS is carried out. In Section III, the proposed algorithm is presented along with its mathematical formulas followed by performance evaluation through computer simulations in section IV. Conclusions are drawn in Section V.

2. SYSTEM MODEL

A cognitive network consisting of \( N \) CUs is considered. All CUs try to access a target spectrum, called primary spectrum. The primary spectrum is licensed for a set of users called primary users (PUs). All the stages of the cognitive transmission is organized by a central FC located at the base station. The channels between the CUs and the licensed users (sensing channels) and the channels between the CUs and the FC (reporting channels) are modelled as narrow-band Rayleigh fading with additive white Gaussian noise (AWGN). The channel variance between any CU and the target spectrum is denoted by \( \mu^2 \), while the channel variance between any CU and the FC is denoted as \( \sigma^2 \). The CUs are distributed randomly around the FC. The distance between \( i \)th CU and the FC, denoted as \( d_i \), is uniformly distributed \( d_i \sim U[d_{\min}, d_{\max}] \), where \( d_{\min} \) and \( d_{\max} \) are the minimum and the maximum distances, respectively.

As depicted in Figure 1, during spectrum sensing, the target spectrum is sensed for a specific time, denoted by \( T_s \). The optimal method for spectrum sensing is energy detection method especially when no prior information is available (Cabric, Mishra & Brodersen, 2004). This method implies collecting a number of samples and computing the average energy contained in these samples. According to the HS, the resultant average is compared to a predefined threshold, and a local binary decision \( u_i \{1, 0\} \) about spectrum status is made. If \( u_i = 1 \) then the \( i \)th CU decides that the spectrum is being used. Otherwise, the spectrum is identified as unused by the \( i \)th CU.

Figure 1. The general description of cooperative spectrum sensing
The local sensing performance is measured by two probabilities, namely, the detection probability ($P_d$) and the false-alarm probability ($P_f$). The detection probability is the probability of identifying a channel as used given that it is actually used. In other words, making a local decision of $u_i = 1$, when the channel is used. The false alarm probability is the probability of identifying a channel as used channel given that it is unused, which means making a local decision of $u_i = 1$ when the channel is unused.

For simplicity, we assume an identical performance among the CUs, and hence $P_{d1} = P_{d2} = \ldots = P_d$ and $P_{f1} = P_{f2} = \ldots = P_f$. $P_d$ and $P_f$ for Rayleigh fading channels are given as (Ghasemi & Sousa, 2007), (Digham, Alouini & Simon, 2007):

$$P_d = \int_0^\infty Q_m(\sqrt{2mx}, \sqrt{\lambda})f_p(x) \, dx$$

$$P_f = \frac{\Gamma\left(m, \frac{\lambda}{2}\right)}{\Gamma(m)}$$

where $Q_m(\ldots)$ is the generalized Marcum Q-function (Nuttall, 1975), $m$ is the time-bandwidth product, $\rho$ is the signal-to-noise ratio, $f_p(x)$ is the probability density function (pdf) of the Rayleigh fading channel, $\lambda$ is the energy threshold used by the energy detector and $\Gamma(\ldots)$ is the incomplete gamma function (Ryzhik, 1994).

### 3. CONVENTIONAL APPROACH OF COOPERATIVE SPECTRUM SENSING

In the conventional approach of CSS, all CUs should participate in the spectrum sensing process. Therefore, after a local decision is issued individually by each CU, all local decisions should be reported to the FC. The general FR to process the received local decisions in HS is called $K-out-of-N$ rule (Althunibat, Di Renzo & Granelli, 2013), where $N$ denotes the total number of reporting users and $K$ represents the number of users who detect a signal in the target spectrum, i.e., have obtained a local decision of 1. $K-out-of-N$ rule implies comparing $K$ with a predefined threshold ($K'$). If $K \geq K'$, then the spectrum is identified as used. Otherwise, the spectrum is identified as unused. Mathematically, the function of $K-out-of-N$ rule is written as follows:

$$FinalDecision = \begin{cases} used & \text{if } K \geq K' \\ unused & \text{if } K < K' \end{cases}$$
Energy-Efficient Cooperative Spectrum Sensing for Cognitive Radio Networks

Some popular rules are derived from this rule like OR-rule ($K' = 1$), AND-rule ($K' = N$). Without loss of generality, we consider only OR-rule ($K' = 1$). The overall performance is measured by the overall detection probability and the overall false alarm probability, which are given for OR-rule as (Viswanathan & Varshney, 1997) (Ghasemi & Sousa, 2007):

$$P_D = 1 - (1 - P_d)^N$$

$$P_f = 1 - (1 - P_f)^N.$$  

Regarding the total energy consumed in this approach, if we denote the energy consumed by the $i^{th}$ CU during sensing and reporting by $E_{s,i}$, $E_{r,i}$, respectively, and the energy consumed by the scheduled user is $E_t$, the total energy consumed is given as:

$$E_{tot} = \sum_{i=1}^{N} E_{s,i} + \sum_{i=1}^{N} E_{r,i} + P_{unused}E_t$$

where $P_{unused}$ is the probability of identifying the spectrum as unused, and is given as:

$$P_{unused} = 1 - P_0 P_f - P_1 P_d$$

where, $P_0$ and $P_1$ are the probabilities that the spectrum is actually unused and used, respectively.

Notice that the sensing energy is identical for all CUs and equal to $E_s$, thus, (6) can be simplified as:

$$E_{tot} = NE_s + \sum_{i=1}^{N} E_{r,i} + P_{unused}E_t.$$  

As the energy is defined as the consumed power multiplied by the time, (8) can be rewritten as:

$$E_{tot} = N\alpha_s T_s + \sum_{i=1}^{N} \alpha_{r,i} T_r + P_{unused}\alpha_t T_t$$

where: i) $T_s$, $T_r$, and $T_t$ are the time consumed by a CU in sensing, reporting and transmission, respectively; ii) $\alpha_s$, $\alpha_r$, and $\alpha_t$ are the consumed power during sensing, reporting and transmission, respectively.

Another important quantity that should be defined is the amount of the successfully transmitted data ($D$) measured in bits. Notice that D depends on the correct identification of the unused spectrum. $D$ is given as:

$$D = \sum_{i=1}^{N} \alpha_{r,i} T_r + P_{unused}\alpha_t T_t$$
\[ D = P_0(1 - P_F)R T_i \] (10)

where \( R \) is the data rate in bps, and the factor \( P_0(1 - P_F) \) represents the probability of the correct identification of the unused spectrum. From (10), it is also clear that the \( D \) increases as \( P_F \) decreases.

Finally, for the purpose of assessing the energy efficiency in \([\text{Joule / bit}]\), we define the consumed energy per bit (\( EpB \)) as follows:

\[ EpB = \frac{E_{tot}}{D} \] (11)

4. THE PROPOSED APPROACH

Motivated by improving the energy efficiency in cognitive radio systems, we propose a novel approach for spectrum sensing which reduces energy consumption during this process with a constraint on the achievable detection accuracy. The idea is to reduce the number of users participating in spectrum sensing, which results in a partial cooperative spectrum sensing. The novelty of our proposal is that the participation decision is taken individually by each CU, and on a base of expected energy consumption. In other words, each CU calculates its expected energy consumption in case of participating in spectrum sensing, and compares it to a predefined threshold (\( \gamma \)). If it is lower than \( \gamma \), the CU will participate. Otherwise, the CU will not participate. The participation threshold is identical for all CUs, and it is decided at the FC and broadcasted to CUs. By such mechanism, we try to reduce energy consumption by an effective way that implies preventing the CUs who will consume large amount of their energy in spectrum sensing from participation.

If we denote the estimated energy consumed during spectrum sensing by the \( i^{th} \) CU by \( E_i \), the following equation describes the participation decision (\( S_i \)):

\[
S_i = \begin{cases} 
1 \text{ (Participate)} & \text{if } E_i < \gamma \\
0 \text{ (Don't participate)} & \text{if } E_i \geq \gamma 
\end{cases}
\] (12)

Next, we discuss the calculation of \( E_i \), the resulting performance based on our proposal, and finally, we address the energy efficiency improvement achieved by the proposed approach.

4.1 Calculation of \( E_i \)

\( E_i \) includes the energy consumed during local sensing and decision reporting by the CU. Thus, \( E_i \) is given as:

\[ E_i = E_s + E_{r,i} \] (13)
As $E_s$ is identical for all CUs, then the determinant factor in $E_i$ is $E_{r,i}$ that can be written as a product of the reporting time $T_r$ and the power consumed during reporting $\alpha_{r,i}$, as follows:

$$E_{r,i} = \alpha_{r,i} T_r$$  

(14)

In results’ reporting, the user is in transmission status, and hence, $\alpha_{r,i}$ mainly depends on the distance from the FC and the desired bite error rate. $\alpha_{r,i}$ is given as (S. Cui, 2004):

$$\alpha_{r,i} = \alpha^c + \alpha_{PA}^i$$  

(15)

where $\alpha_{PA}^i$ is the power consumed in the power amplifier stage of the $i^{th}$ user, and $\alpha^c$ is the power consumed by the other circuit elements. $\alpha^c$ is identical in all users and can be modelled as:

$$\alpha^c = \alpha^{DAC} + \alpha^{filt} + \alpha^{mix} + \alpha^{sym}$$  

(16)

where $\alpha^{DAC}$, $\alpha^{filt}$, $\alpha^{mix}$, and $\alpha^{sym}$ are the power consumption at the digital-to-analog converter (DAC), the transmit filters, the mixer, and the frequency synthesizer, respectively. $\alpha^{filt}$, $\alpha^{mix}$, and $\alpha^{sym}$ can be modelled as constants, while $\alpha^{DAC}$ can be approximated as:

$$\alpha^{DAC} = \left(\frac{1}{2}V_{dd}I_0(2^{n_1} - 1) + n_1 C_p (2B + f_{cor})V_{dd}^2\right)$$  

(17)

where $I_0$ is the current supply, $n_1$ is the number of bits in the DAC, $C_p$ is the parasitic capacitance, $V_{dd}$ is the voltage supply, $f_{cor}$ is the corner frequency, and $B$ is the symbol bandwidth. The second part of (15), $\alpha_{PA}^i$ is given as:

$$\alpha_{PA}^i = \frac{\zeta}{\delta} \alpha_{out}^i$$  

(18)

where $\delta$ is the drain efficiency of the RF power amplifier, $\zeta$ is the Peak-to-Average Ratio (PAR) which is dependent on the modulation scheme and the constellation size, and $\alpha_{out}^i$ is the transmitted power from the amplifier. When the channel only experiences a square-law path loss we have:

$$\alpha_{out}^i = E_b^b R_b$$  

(19)

where $E_b^b$ is the required energy per bit at the receiver for a given BER requirement, and $R_b$ is the bit rate. Under Rayleigh fading, $E_b^b$ in (19) for BPSK modulation can be given as follows:
where $P_e$ is the BER and $\sigma_i^2$ is channel variance that is given as:

$$\sigma_i^2 = \frac{(4\pi d_i)^2}{G_i G_r \lambda^2 M_f N_f}$$

where $G_t$ is the transmitter antenna gain, $G_r$ is the receiver antenna gain, $\lambda$ is the carrier wavelength, $M_f$ is the link margin compensating the hardware process variations and other additive background noise or interference. $N_f$ is the receiver noise figure defined as $N_f = \frac{N_o}{N_r}$, with $N_o = -171$ dBm / Hz the single-sided thermal noise Power Spectral Density (PSD) at room temperature. $N_r$ is the PSD of the total effective noise at the receiver input.

In addition to multipath fading, the performance of cooperative wireless networks is also affected by shadowing in realistic operating conditions. Recently several studies have been conducted to analyze the impact of shadowing in CSS (Di Renzo, Imbriglio, Graziosi & Santucci, 2009), (Di Renzo Graziosi & Santucci, April 2009), (A. Ghasemi, 2007 January). In general, all these studies have concluded that shadowing significantly reduces the performance of CSS. As such, our proposed partial CSS approach is also not free from the impacts of shadowing. Usually, shadowing is modelled using log-normal distribution (Alouini, 2005).

A composite shadowing/multipath fading environment consists of shadowing superimposed on multipath fading environment. In the case of a composite log-normal shadowing/Rayleigh fading channel, with BPSK modulation, the BER can be obtained from (Eq. 5.27, Alouini, 2005) as follows:

$$P_e = \frac{1}{\sqrt{2\pi}} \sum_{n=1}^{N} w_n \left[ 1 - \sqrt{\frac{c_n}{1 + c_n}} \right]$$

where $c_n = 10^{(x_n \sqrt{2} \gamma + 10 \log_{10} \gamma) / 10}$, $\gamma = (E_b/N_o) \sigma_i^2$, $\Omega$ is the logarithmic standard deviation of shadowing, and $\{x_n\}$ and $\{w_n\}$, with $n = 1, 2, ..., N$, are the zeros and weights of the $N$ th-order Hermite polynomial, respectively (Table 25.10, Stegun, 1972). For the ease of illustration of the optimization scheme, in the subsequent analysis, the affects of shadowing have not been not considered. More specifically, we only assume independent and identically distributed Rayleigh fading channels. However, the interested readers may extend our proposed approach to include shadowing by taking into account that the expression for $\bar{E}_b$ in (20) must be replaced by $\bar{E}_b$ obtained from (22).
4.2 The Achievable Performance

Let us consider the estimated energy of each CU \( (E_i) \) as a random variable with a Probability Density Function (pdf), \( f_i \), and Cumulative Distribution Function (CDF), \( F_{E_i} \). Therefore, for any CU, the probability of participation in the spectrum sensing equals to \( F_{E_i}(\gamma) \). Also, the number of CUs who have decided to participate \( (N^*) \) follows a binomial distribution described as:

\[
Prob(N^* = n) = \binom{N}{n} (F_{E_i}^*(\gamma))^n (1 - F_{E_i}(\gamma))^{N-n}
\]

where the average number of sensing users \( \bar{N}^* \) is given by:

\[
\bar{N}^* = NF_{E_i}(\gamma)
\]

After reporting the local decisions made by \( \bar{N}^* \) CUs, OR-rule is applied and a final decision is made. In case of \( N^* = 0 \), i.e., no users have participated, a random final decision is made at the FR. Therefore, the average overall detection probability \( (P_{D}^*) \) and the average overall false alarm probability \( (P_{F}^*) \) can be written as:

\[
P_{D}^* = \begin{cases} 
1 - (1 - P_s)^{N^*} & \text{if } N^* \geq 1 \\
0.5 & \text{if } N^* = 0
\end{cases}
\]

\[
P_{F}^* = \begin{cases} 
1 - (1 - P_f)^{N^*} & \text{if } N^* \geq 1 \\
0.5 & \text{if } N^* = 0
\end{cases}
\]

where \( N^* = 1, 2, ..., N \).

4.3 Energy Efficiency Optimization

The total energy consumed by the whole system by following the proposed approach \( (E_{tot}^*) \) can be written as follows:

\[
E_{tot}^* = \sum_{i=1}^{N} S_i E_i + P_{used}^* E_i^*
\]
where the first term represents the consumed energy during spectrum sensing process, which equals to 0 for the CUs who have not participated because it is multiplied by \( S_i = 0 \). The second term represents the energy consumed during data transmission \( E_t' \) which is conditioned by \( P_{unused}^* \). \( P_{unused}^* \) is the probability of identifying the spectrum as unused in our approach, which can be obtained by substituting \( P_D^* \) and \( P_F^* \) instead of \( P_D \) and \( P_F \) in (7).

Regarding the calculation of \( E_t' \), we assume that a CU is randomly scheduled for data transmission. Therefore, the calculation of \( E_t' \) follows the same procedure as \( E_t \) with a proper substitution of the values of \( f_{cor} \), \( B \), and \( P_e \).

The amount of successfully transmitted data in bits, \( D^* \) depends mainly on the performance of the spectrum sensing, and can be given as:

\[
D^* = RT\left(P_0(1 - P_F^*)\right)
\]

Hence, the total energy consumed per successfully transmitted bit based on the proposed approach \( E_pB^* \) is given as:

\[
E_pB^* = \frac{E_{tot}^*}{D^*}
\]

Remember that the resulting \( E_pB \) depends mainly on the number of participating users which is a function of \( \gamma \). Therefore, in order to minimize \( E_pB^* \), an optimization of \( \gamma \) is required.

## 5. SIMULATION RESULTS

In this section, we present some simulation results in order to illustrate the advantage of the proposed partial-cooperative spectrum sensing scheme. The considered N CUs are randomly distributed around the FC, each at a distance that is uniformly distributed between 0.1 Km to 7 Km. In particular, we are interested in finding an optimal value of the energy threshold, \( \gamma \), which minimizes the total energy consumed per successfully transmitted bit in partial CSS, \( E_pB^* \). Table 1 lists the simulation parameters used in this section.

Figure 2 shows the average number of participating CUs in CSS versus the participation threshold \( \gamma \). The x-axis is shown in terms of \( E_{min}^* \), \( E_{max}^* \), and \( \Delta \), where \( E_{min}^* \) and \( E_{max}^* \) are the energy consumed in spectrum sensing by a CU at a distance equals to \( d_{min} \) and \( d_{max} \), respectively. \( \Delta \) is the step between each two consecutive lines equals to \( 1 \times 10^{-14} \). Obviously, as \( \gamma \) increases, the probability of participating in CSS for each CU increases as well, and hence, the number of participating will increase. Different numbers of available CUs in the network are shown in Figure 2. However, such change in the participating CUs will undoubtedly influence the transmitted data, energy consumption and energy efficiency, as we will see in the next results.
As the number of participating CUs is variable depending on the participation threshold, it is expected that both the false alarm and detection probabilities will be affected. In order to show the effect of the participation threshold on the sensing accuracy, we use the false-decision probability (δ) as an evaluation metric. δ is defined as the weighted sum of false alarm probability and the missed detection probability as follows:

$$\delta = P_0 P_f + P_f (1 - P_0)$$  \hspace{1cm} (30)

Figure 3 plots the false-decision probability versus participation threshold at N=10. At low values of the participation threshold, δ is equal to 0.5 since the decision is random when no CUs participate in the CSS process. Optimizing the participation threshold yields in a minimum false-decision probability as shown in Figure 3. Notice that the minimum false-decision probability attained by our approach is much less than the attained by the conventional approach.

### Table 1. Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>10</td>
<td>(P_0)</td>
<td>0.5</td>
</tr>
<tr>
<td>(P_d)</td>
<td>0.8</td>
<td>(P_f)</td>
<td>0.2</td>
</tr>
<tr>
<td>(T_s)</td>
<td>3 ms</td>
<td>(T_r)</td>
<td>0.01 ms</td>
</tr>
<tr>
<td>(T_i)</td>
<td>40 ms</td>
<td>(d_{\text{min}})</td>
<td>100 m</td>
</tr>
<tr>
<td>(d_{\text{max}})</td>
<td>7 Km</td>
<td>(\alpha_s)</td>
<td>106 mW</td>
</tr>
<tr>
<td>(\alpha_{\text{syn}})</td>
<td>50.0 mW</td>
<td>(\alpha_{\text{filt}})</td>
<td>2.5 mW</td>
</tr>
<tr>
<td>(\alpha_{\text{mix}})</td>
<td>30.3 mW</td>
<td>(I_0)</td>
<td>3 (\mu A)</td>
</tr>
<tr>
<td>(V_{dd})</td>
<td>3 V</td>
<td>(f_r)</td>
<td>2.5 GHz</td>
</tr>
<tr>
<td>(R_b)</td>
<td>10 Kbps</td>
<td>(n_1)</td>
<td>10</td>
</tr>
<tr>
<td>(C_p)</td>
<td>1 pF</td>
<td>(G_t G_r)</td>
<td>5 dBi</td>
</tr>
<tr>
<td>(N_f)</td>
<td>10 dB</td>
<td>(M_i)</td>
<td>40 dB</td>
</tr>
<tr>
<td>(\delta)</td>
<td>0.35</td>
<td>(f_{\text{corr}})</td>
<td>1 kHz</td>
</tr>
<tr>
<td>(P_e)</td>
<td>(10^{-5})</td>
<td>(\zeta)</td>
<td>(514 \times 10^{-3})</td>
</tr>
</tbody>
</table>
Figure 2. The average number of participating CUs versus $\gamma$ ($\Delta = 1 \times 10^{-14}$)

The achievable amount of successfully transmitted data versus the threshold $\gamma$ is shown in Figure 4. For low values of $\gamma$, all CUs will not participate in CSS since they have $E_i$ larger than $\gamma$, which results in $P_f^* = 0.5$, according to (26). Hence, $D^*$ is constant since it depends mainly on $P_f^*$, as stated in (28).

When $\gamma$ increases so that the number of sensing users equals $1$, $P_f^*$ improves, and consequently, the transmitted data increases. As $\gamma$ increases, $D^*$ decreases since $P_f^*$ increases. For comparative purposes, Figure 4 also shows the plot for the achievable amount of successfully transmitted data using the conventional approach, $D$, where all the users take part in CSS. Since in conventional approach, $D$ is independent of the value of $\gamma$, the plot will be a constant with respect to $\gamma$. 
In Figure 5, the total energy consumed by the system in partial CSS, \( E_{\text{tot}}^* \) over different values of \( \gamma \) is plotted. We can see that, as \( \gamma \) increases, \( E_{\text{tot}}^* \) first remains the same, but then decreases and then gradually becomes stable for larger values of \( \gamma \). The initial flat region in the plot is due to the fact the estimated energy, \( E_i \) of all the CU’s is above \( \gamma \). Hence, all the CU’s will not participate in spectrum sensing, and energy is consumed only in transmission. As \( \gamma \) is increased, \( E_{\text{tot}}^* \) decreases even though more CUs participate in CSS. This is due to the decrease in \( P_{\text{snr}} \). The plot for total energy consumed by the system in conventional approach is also shown in Figure 5.

Figure 3. The false decision probability versus \( \gamma \) \((\Delta = 1 \times 10^{-14})\)
From the previous figures, it is clear that increasing $\gamma$ lowers the energy consumption but with lower transmitted data. Thus, in order to find the optimal value of $\gamma$ that balances the two contrasting effects, the total energy consumed per successfully transmitted bit in partial CSS, $E_{pB^*}$ versus different values of $\gamma$ is plotted in Figure 6. As $\gamma$ increases, $E_{pB^*}$ first remains the same, but then decreases and then increases after a particular value of $\gamma$. The value of $\gamma$, where $E_{pB^*}$ is minimum gives the optimal value of $\gamma$. The plot for total energy consumed per successfully transmitted bit is also shown in Figure 6. The results in Figure 6 clearly show the potential gain of using the proposed partial-CSS scheme over the conventional approach. More precisely, when the optimal value of $\gamma$ is used, partial CSS provides a Relative Average Energy Reduction (RAER) per successfully transmitted bit of approximately 78% with respect to the conventional approach.
The threshold $\gamma$ plays a key factor in the performance of the proposed approach. In Figure 7, we plot the percentage of RAER compared to the conventional approach versus the total number of CUs, where RAER is expressed as follows:

$$\text{RAER}[^\%] = \frac{E_{PB}^{\text{conventional}} - E_{PB}^{\text{proposed}}}{E_{PB}^{\text{conventional}}} \times 100$$

(30)
6. CONCLUSION

A partial cooperative spectrum sensing approach is presented in this chapter, which aims at reducing the energy consumption in cognitive radio. The proposed approach is based on reducing the number of sensing users. Each user decides to participate in spectrum sensing if its expected energy consumption during this process is less than a threshold. The participation threshold is optimized to minimize the energy consumption through computer simulations.

As a future work, the performance of the proposed approach can be investigated considering non-identical local sensing performance and channel conditions among users. Also, the influence of shadowing

Figure 6. Total energy consumed per successfully transmitted bit versus $\gamma$ ($\Delta = 1 \times 10^{-11}$)
in sensing and reporting channels on the overall performance is worth to be studied. Another possible future work is to extend the proposed approach to a fully-distributed approach. The fully-distributed approach implies that the participation threshold is locally decided at each CU considering the instantaneous battery status.

ACKNOWLEDGMENT

This work was supported by the European Commission under the auspices of the FP7–PEOPLE MITN–GREENET project (grant 264759).
REFERENCES


Energy-Efficient Cooperative Spectrum Sensing for Cognitive Radio Networks


Energy-Efficient Cooperative Spectrum Sensing for Cognitive Radio Networks


KEY TERMS AND DEFINITIONS

Cognitive Radio Networks: A type of wireless networks that consists a set of users cooperating to use a specific spectrum based on cognitive radio technology.

Cognitive Radio: A wireless technology proposed to improve spectrum efficiency. It is based on exploiting the temporarily unused portions of the spectrum by unlicensed users.

Cooperative Spectrum Sensing: An approach proposed to enhance the reliability of the spectrum sensing process. It implies sharing the local sensing results of several users at a central entity, aiming at improving the reliability of the process decision.

Energy Efficiency: The ratio of the average successfully transmitted data in bits to the average consumed energy in Joule.

Spectrum Sensing: A method used to identify the spectrum status either used or unused.

Wireless Communications: The transfer of data between two or more devices that are not electrically connected to each other.

Wireless Networks: A type of communication networks that uses wireless data transfer techniques.

ENDNOTES

1 A closed form expression of the integral in (1) can be found in (Digham et al., 2007)