An Energy Minimization Algorithm for Cooperative Spectrum Sensing

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***Abstract*—We introduce an algorithm minimizing the consumed energy of a cooperative spectrum sensing-based cognitive radio network. The energy is minimized, while satisfying requirements for primary user protection and for secondary user data rate simultaneously, with respect to the powers for transmitting on control and data channels, the number of reported bits, and the thresholds of the global sensing test. Control and data channels are assumed not to be error-free. Simulation results finally confirm our claims.**

I. Introduction

Secondary access to licensed spectrum band which is implemented by cognitive radio (CR) has been proposed to improve the spectrum utilization for future communication systems. To perform secondary spectrum access, secondary users must know a thorough information of the spectrum usage of the primary system. There are two widespread approaches for characterizing this spectrum usage information: i) the geolocation database [1] and ii) the spectrum sensing [2].

In this paper, we will focus on spectrum sensing. Desperately, individual spectrum sensing at a terminal may not provide good sensing accuracy because of deep shadowing or fading. To overcome this shortcoming, collecting sensing information from multiple terminals through a process called cooperative spectrum sensing (CSS) to improve the reliability of sensing decision has been considered in several studies [3]–[5]. However such a cooperative process requires more time and energy to collect sensing data. The problem of consuming energy may be severe if wireless CR users are equipped with limited battery. Therefore, minimizing total consumed energy of both cooperative spectrum sensing and data transmission while keeping the sensing accuracy and data throughput should be investigated.

There are some previous works which considered to minimize of consumed energy. In [3], the energy for CSS is reduced by grouping closed CR users into clusters and reporting sensing data to a closer cluster head instead of sending directly to fusion center (FC). The sensing results of a cluster are then compressed into cluster's sensing result which may decrease the accuracy of sensing process and make the organization of the network being too complex to be optimized. In [5], [6], energy for reporting sensing data is lessened by adopting censoring techniques, and in [4], the authors maximize energy efficiency which was intuitively defined by the ratio between the average throughput and the average consumed energy. In [7], the quantizer and power allocation between users are optimized under a total power constraint. Though it has been shown in those studies that the consumed energy can be improved, the data transmitting energy is not investigated. Moreover the influence of the number of bits for sensing data and the channels errors on the consumed energy while maintaining sensing accuracy and data rate is not described.

In this paper, we minimize the total consumed energy in both CSS and data transmission process under both reporting and data channel errors circumstance with a multi-bit/soft-based fusion rule while keeping satisfying sensing performance and minimum data rate of CR network. The data rate is given by the throughput of the considered link. The parameters to be optimized are: i) the number of bits used for representing local sensing data which affects not only the sensing accuracy but also the time and the energy for reporting; ii) the power for reporting data which drives the accuracy of sensing, hence the throughput, and the total consumed energy; iii) the power for transmitting data which determines both the total energy and output throughput; iv) the threshold of the test.

II. Problem statement

We consider a CR network with K users. Opportunistic spectrum access for sharing spectrum band with a primary system is adopted. At a certain operation time, one secondary user, let say k_0, sends a request to the FC to use the spectrum hole for transmitting data at a target data rate $\eta^{(t)}$.

In order to analyze the spectrum hole, the FC requires K users in the network to perform cooperative spectrum sensing process. The cooperative sensing scheme includes two steps: the local sensing the channel of interest at CR users,and the reporting sensing results to the FC to make a final decision on primary user state. The FC has to estimate parameters of the cooperative sensing as well as the data transmission processes such as number of reported bits, and reporting and data transmitting powers so that the consumption energy is minimized while the requirements of primary system protection and target data rate are satisfied simultaneously.

Therefore, we use the following assumptions: 1) Energy detection method is considered at the local sensing step because of its simple implementation and its robustness to unknown information of the source signal and channel conditions [8]. 2) The reporting is done through a control channel with a fixed

978-1-4673-6540-6/15/$31.00 © 2015 IEEE

limited bandwidth [6], [9]. As any orthogonal multiple access method (TDMA, FDMA, CDMA) offers the same spectral efficiency, they can be used equivalently. For the simplicity of the presentation, we consider TDMA scheme. 3) Both the reporting and the data channels are suffered from errors. For the sake of simplicity, we assume they are AWGN channels, but the extension to other types of channels (such as Rayleigh one) is possible. For instance, if Rayleigh fading channels is considered, then closed-form expresions in Eqs. (5), (11), and (17) have to be modified accordingly. But the methodology of the approach is identical. Fig. 1 shows the structure of the

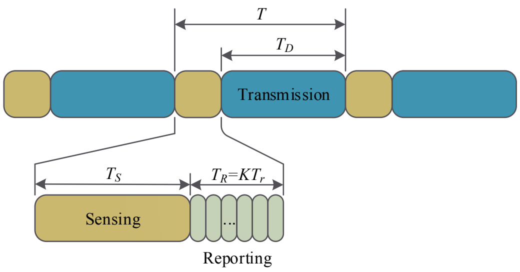

Figure 1. Frame structure of the CR network

frame. We thus can define the following parameters: T is the frame duration, T_S is the sensing time duration, T_R is the reporting time duration, T_D is the data time duration, $P_R(k)$ is the power used for reporting sensing information from the k-th user to the FC, and P_D is the power used for transmitting data of user k_0.

As we focus on energy efficiency, we would like to minimize the energy consumption during one frame described in Fig. 1 of duration T. So our optimization problem is

$$\begin{array}{ll} \min_{\boldsymbol{\theta}} & E = \frac{1}{K}\sum\limits_{k=1}^{K} P_R(k)T_R + P_D T_D p_{cf} \\ & \mathbf{C1}: T_S + T_R + T_D = T, \\ s.t. & \mathbf{C2}: \eta \geq \eta^{(t)}, \\ & \mathbf{C3}: p_d \geq p_d^{(t)} \end{array} \quad (1)$$

where

- p_{cf} is the probability that the spectrum sensing step returns the answer “channel is free” and so the channel can be used for data transmission. The term p_{cf} can actually be decomposed as follows

$$p_{cf} = \pi_0(1-p_f) + (1-\pi_0)(1-p_d) \quad (2)$$

  where π_0 is a prior probability of absence of primary user, and p_f and p_d are the probabilities of false alarm and probability of detection of the cooperative spectrum sensing process at the FC (these probabilities will take into account the quantization of the local test result and the reporting channel errors).
- η is the throughput of user k_0 when transmitting data.
- $p_d^{(t)}$ is the target for primary user detection probability.
- $\boldsymbol{\theta} = [\beta, \{P_R(k)\}_k, P_D, \tau^{(\beta)}]$ is the parameters vector to be optimized as mentioned at the end of Section I. β corresponds to the number of bits after the quantization step. $P_R(k)$ is the power used by user k for reporting the information to the FC. P_D is the power consumed by the secondary user k_0 for sending data, and $\tau^{(\beta)}$ is the threshold for the global test at the FC.

We remark the following:

- **C1** and **C3** is associated with the frame duration length and the requirement of protecting operation of primary system, respectively.
- **C2** is related to the data rate required by the secondary user k_0. Since the throughput of the user k_0 depends not only on $\boldsymbol{\theta}$ but also on the uncontrollable primary user activity, the data rate constraint sometimes cannot be fulfilled. In that case, the best selection of the secondary user is to move to an other channel where the primary activity, i.e., evaluated via $1-\pi_0$, is lower.
- The energy consumed for implementing the sensing test is neglected.

To solve (1), the information of sensing capabilities, i.e., the detection probability p_d and the false alarm probability p_f, must be known. Therefore, in the next section, we consider the cooperative sensing scheme and its performance.

III. Cooperative Sensing

A. Local spectrum sensing

Assuming a sampling frequency f_S during the sensing step, we have $N = f_S T_S$ available samples. Assuming AWGN channel, the local spectrum sensing problem at CR user k corresponds to the following a binary hypothesis

$$y_k[n] = \begin{cases} w_k[n], & H_0 \\ s[n] + w_k[n], & H_1 \end{cases}, n = 1, 2, ..., N \quad (3)$$

where $y_k[n]$ is the received signal at time n at the k-th CR user, $w_k[n]$ is the noise and is assumed to be a zero-mean i.i.d. circularly-symmetric complex-valued Gaussian process with variance $\sigma_{w_k}^2$, $s[n]$ is the potential unknown deterministic signal coming from the primary user. H_0 and H_1 represent the hypotheses of the absence and presence of primary signal respectively.

The statistic test of the energy detector is given by $z_k = \sum_{n=1}^{N} |y_k[n]|^2$. In [10], it is shown that z_k has $2N$-degrees of freedom central and non-central chi-squared distribution under H_0 and H_1 respectively. The cumulative density functions (cdf) of the test are thus computed by

$$F_{Z_k|H_0}(z_k|H_0) = P_N(z_k/2) \quad (4)$$

$$F_{Z_k|H_1}(z_k|H_1) = 1 - Q_N\left(\sqrt{2N\gamma_k}, \sqrt{z_k}\right) \quad (5)$$

where $Q_N(.,.)$ denotes the generalized Marcum Q-function, $P_N(b) = \gamma(N,b)/\Gamma(N)$ with the gamma function $\Gamma(.)$ and the incomplete gamma function $\gamma(.,.)$, where $\gamma_k = E_s/\sigma_{w_k}^2$ is the SNR of the received signal at the k-th user with the symbol variance E_s.

After the sensing period, each energy test z_k is reported to a FC where a squared-law combining is adopted. The global test with the global decision threshold τ is thus given by

$$Z = \sum_{k=1}^{K} z_k \underset{H_0}{\overset{H_1}{\gtrless}} \tau. \quad (6)$$

B. Quantized cooperative sensing

Time, bandwidth and energy are required for reporting a raw z_k. Hence, communicating with the FC by a quantized version of the energy test statistics which corresponds to work with a multi-bit decision at the local nodes is more practical.

Therefore, z_k in Eq. (6) is replaced with its β-bit quantized version. As a result, the practical test at the FC is given by

$$Z^{(\beta)} = \sum_{k=1}^{K} z_k^{(\beta)} \underset{H_0}{\overset{H_1}{\gtrless}} \tau^{(\beta)}, \quad (7)$$

where $z_k^{(\beta)} = Q_k^{(\beta)}(z_k)$ is the quantized version of z_k and $Q_k^{(\beta)}$ denotes a β-bit quantizer associated with the k-th user. Let $M = 2^\beta$ be the number of quantization levels. Let $\{t_{k,i}\}_{i=0}^{M}$ and $\{L_{k,j}\}_{j=1}^{M}$ be the set of thresholds and the set of quantization levels for $Q_k^{(\beta)}$ respectively. As the support of the pdf of z_k is $\mathbb{R}_+$, we have $t_{k,0} = 0$ and $t_{k,M} = +\infty$. Moreover, the i-th quantization region is denoted by $\Re_{k,i} = [t_{k,i-1}, t_{k,i})$ with $i = 1, \cdots, M$. The quantization level is usually the central point of the quantization region. Thus,

$$L_{k,i} = \frac{1}{S_{k,i}} \int_{\Re_{k,i}} z f_{Z_k}(z) dz \quad (8)$$

where $S_{k,i} = \int_{\Re_{k,i}} f_{Z_k}(z)dz$ and $f_{Z_k}(z) = \pi_0 f_{Z_k|H_0}(z) + (1-\pi_0) f_{Z_k|H_1}(z)$, with $f_{Z_k|H_j}$, $j = 0,1$, the probability density function (pdf) of the test under hypothesis H_j.

For the sake of simplicity, we only consider the maximum entropy quantizer [11]. Other kind of quantizers can be adopted easily. The quantization thresholds of the maximum entropy quantizer $t_{k,i}$ are defined by $S_{k,i} = 1/M, \forall i = 1, ..., M$. Therefore, the probability mass function (pmf) of the quantized $z_k^{(\beta)}$ under H_j at CR user k is equal to

$$f_{z_k^{(\beta)}|H_j}(\ell) = \sum_{i=1}^{M} S_{k,i|H_j} \delta(\ell - L_{k,i}), \quad (9)$$

with $S_{k,i|H_j} = \int_{\Re_{k,i}} f_{z_k|H_j}(z)dz$.

Actually, the test at the FC is done with the *received* quantized local test. As we assume that the reporting channel may occur error, we have to calculate the pmf of the *received* quantized decisions at fusion center which is given by

$$f^{(fc)}_{z_k^{(\beta)}|H_j}(\ell) = \sum_{i=1}^{M} S^{(fc)}_{k,i|H_j} \delta(\ell - L_{k,i}). \quad (10)$$

In order to derive $S^{(fc)}_{k,i|H_j}$, we need a *reporting channel model*. For the sake of simplicity, we assume that the binary phase shift key (BPSK) modulation without forward error coding is adopted. Consequently, the BER of the reporting channel, denoted by p_b, is equal to

$$p_b = Q\left(\sqrt{g(k) P_R(k) \beta / (B_R N_0)}\right) \quad (11)$$

where $g(k)$ is the channel gain between the secondary user k and the FC, B_R is the bandwidth of this channel, β is the number of reported bits, and N_0 is the noise power spectral density. According to [12], we have

$$S^{(fc)}_{k,i|H_j} = \sum_{m=1}^{M} p_b^{d_{i,m}^{(k)}} (1-p_b)^{M-d_{i,m}^{(k)}} S_{k,m|H_j}. \quad (12)$$

where $d_{i,m}^{(k)}$ is the Hamming distance between bit sequences representing levels $L_{k,i}$ and $L_{k,m}$.

It should be noted that the k-th user and the FC need to know the pdf of z_k to perform the quantization and the de-quantization processes. However, the report of this information to the FC will be done seldom since we assume that the coherence time of the statistics of z_k is large enough.

Now, the problem is to determine the global threshold $\tau^{(\beta)}$. Since the test at the FC, given by Eq. (7), is a sum of K local independent tests, the pmf of $Z^{(\beta)}$ under both hypotheses H_j for $j = 0, 1$ can be determined by

$$f_{Z^{(\beta)}|H_j} = f^{(fc)}_{z_1^{(\beta)}|H_j} \star f^{(fc)}_{z_2^{(\beta)}|H_j} \star \cdots \star f^{(fc)}_{z_K^{(\beta)}|H_j}, \quad (13)$$

where $\star$ denotes the convolution operator. Finally, $f_{Z^{(\beta)}|H_j}$ takes the following form

$$\begin{aligned} f_{Z^{(\beta)}|H_j}(\ell) &= \sum_{i_1 \ldots i_K = 1}^{M} S^{(fc)}_{1,i_1|H_j} \ldots S^{(fc)}_{K,i_K|H_j} \delta(\ell - L_{1,i_1} \ldots - L_{K,i_K}), \\ &= \sum_q \psi_{K,q|H_j} \delta(\ell - L_q). \end{aligned} \quad (14)$$

where $\psi_{K,q|H_j}$ and L_q can be computed as suggested in [13].

We remind the false-alarm and the detection probabilities used in our optimization problem of Eq. (1) are the false-alarm and the detection probabilities of the quantization-based test at the FC. Given the pmf of $Z^{(\beta)}$, we have

$$p_f = \sum_{q|L_q \geq \tau^{(\beta)}} \psi_{K,q|H_0}, \quad (15)$$

$$p_d = \sum_{q|L_q \geq \tau^{(\beta)}} \psi_{K,q|H_1}. \quad (16)$$

IV. Problem Solution

Before going further, we need to introduce the *data channel model*. The data rate can be well described by the throughput, denoted by η, since the throughput is able to take into account the mistakes done by the sensing engine and the errors occurring in the reporting and data channels. We consider to use a certain (pre-defined) modulation and coding scheme (MCS) with coding gain γ and rate r. Let E_s be the symbol energy used by user k_0 for transmitting data and E_P be the interference energy due to primary user (if it is active). Consequently the codeword error probability can be written as $p_c^{(0)} = Q(\sqrt{\gamma E_s/N_0})$ if the primary user is absent and $p_c^{(1)} = Q(\sqrt{\gamma E_s/(N_0 + E_P)})$ if the primary user is present. Now, let denote

$$\begin{aligned} C_0 &= 1 - p_c^{(0)} = 1 - Q\left(\sqrt{\gamma G P_D/(B N_0)}\right) \\ C_1 &= 1 - p_c^{(1)} = 1 - Q\left(\sqrt{\gamma G P_D/(B N_0 + P_P)}\right) \end{aligned} \quad (17)$$

where G is the gain of the data channel, P_P is the power received by the secondary receiver from the primary user, and B is the bandwidth of the data channel. According to [4], the throughput is then defined by

$$\eta = r(T_D/T)\left[C_0\pi_0\left(1-p_f\right) + C_1\left(1-\pi_0\right)\left(1-p_d\right)\right] \quad (18)$$

As already-mentioned, the parameters to be optimized are $\boldsymbol{\theta} = [\beta, \{P_R(k)\}_k, P_D, \tau^{(\beta)}]$. By remarking that $T_R = K\beta/B_R$, the optimization problem in (1) can be re-written as

$$\begin{aligned} \min_{\boldsymbol{\theta}} \quad & E = \frac{\beta}{B_R}\sum_{k=1}^{K} P_R(k) + \left(T - T_S - \frac{K\beta}{B_R}\right) P_D p_{cf} \\ \text{s.t.} \quad & \mathbf{C1}: T_S + K\beta/B_R + T_D = T \\ & \mathbf{C2}: \eta \geq \eta^{(t)}, \\ & \mathbf{C3}: p_d \geq p_d^{(t)} \end{aligned} \quad (19)$$

First of all, as we do not know in advance which sensor may have a stronger influence on the cooperative spectrum sensing performance, we force each sensor to have the same reporting channel performance. Therefore, we assume that the received reporting power at the FC, denoted by $P_R^{(fc)}$, is the same for all sensors. This implies that

$$P_R(k) = \frac{P_R^{(fc)}}{g(k)} = \frac{B_R N_0 (Q^{(-1)}(p_b))^2}{\beta g(k)}. \quad (20)$$

Hence, we now just have to find $P_R^{(fc)}$ instead of $P_R(k)$ for $k = 1, \cdots, K$. To do that, Channel State Information at the Transmitter for the AWGN reporting channel is required. Thus, the parameters to be optimized boil down to $\boldsymbol{\theta} = [\beta, P_R^{(fc)}, P_D, \tau^{(\beta)}]$.

The parameters to be optimized in (19) include two discrete ones, i.e., β and $\tau^{(\beta)}$, and two continuous ones, i.e., ${P_R}^{(fc)}$ and P_D. In order to adopt a grid search method with reasonable computational load, we first would like to find appropriate range. Concerning $P_R^{(fc)}$, it has been shown [12] that the effect of reporting channel errors on the sensing performance can be neglected if $p_b <$. Therefore, $P_R^{(fc)}$ could be smaller than $P_R^{\max}$ with $P_R^{\max} = B_R N_0 (Q^{(-1)}(10^{-2}))^2/\beta$. Concerning P_D, it is obvious that increasing P_D will decrease the codeword error probability and hence will increase the throughput. But increasing P_D too much will have a strong negative impact on the total consumed energy. Therefore, it is reasonable to upper-bound the value of P_D to $P_D^{\max}$ where $P_D^{\max}$ ensures a quasi-error-free data transmission even in presence of interference. We thus choose $P_D^{\max}$ such that $p_c^{(1)} = 10^{-9}$. Concerning β, it has also been shown in [12] that reporting a few bits are enough, so, we can upper-bound β by a certain threshold $\beta_{\max}$.

Finally, we use the sub-optimal searching algorithm for solving the optimization problem by adopting the search step of δ_R and δ_D for $P_R^{(fc)}$ and P_D combining with the discrete search of β and $\tau^{(\beta)}$ as described in **Algorithm 1**.

V. Numerical results

We assume a 6-nodes CR network. The SNR values of primary signal received at each node are -20, -18, -16, -14, -12, and -10 dB. The length of a frame T is 2 ms. The sampling frequency f_S is 6 MHz. The reporting rate $R_R = 1/B_R$ is 100 Kbps. The number of sensing samples N is 500, and the probability of absence primary user π_0 is 0.5. The distances between CR users and FC are identical and equal to 250 m, and the path-loss exponent is 3.5. The network uses BPSK for the reporting channel and uses QPSK for the data channel with coding rate $r = 3/4$. We fix also $\beta_{\max} = 10$. Unless otherwise stated, we have $p_d^{(t)} = 0.9$.

In Fig. 2, E is plotted with respect to P_D and $\tau^{(\beta)}$ when $\beta = 2$, and $P_R^{(fc)} = 10$ mW. We observe that E is an increasing function of P_D and $\tau^{(\beta)}$ when both other parameters are fixed. Moreover, E also increases when the throughput requirement $\eta^{(t)}$ increases and one of two parameters (P_D or $\tau^{(\beta)}$) is fixed.

In Fig. 3, E is plotted with respect to $P_R^{(fc)}$ when $\beta = 2$, and P_D and $\tau^{(\beta)}$ are chosen such that E is minimized while constraints **C2** and **C3** are satisfied. We see that E exhibits a minimum value according to $P_R^{(fc)}$. The reason is that when $P_R^{(fc)}$ is too small or too high, the energy is high due to the weak accuracy of the sensing or the increase of the reporting energy, respectively.

In Fig. 4, E is plotted with respect to β when $P_R^{(fc)}$ is 10mW, and P_D and $\tau^{(\beta)}$ are chosen such that E is minimized while constraints **C1**, **C2** and **C3** are satisfied. Similarly to Fig. 3, there is an optimal point of β. It can be explained by the dependency of the number of bits on the reporting energy, and on the sensing accuracy, i.e., the data transmitting energy. Indeed, with high β, the total energy for reporting will be high,

Algorithm 1 Find $[\beta_*, P_{R*}^{(fc)}, P_{D*}, \tau_*^{(\beta)}]$

$E_{\min} \leftarrow +\infty$
for $\beta = 1$ **to** $\beta_{\max}$ **do**
  Compute $f_{z_k^{(\beta)}|H_j}$ for $j = 0, 1$ based on Eq. (9)
  for $P_R^{(fc)} = 0 : \delta_R : P_R^{\max}$ **do**
    Compute $f_{z_k^{(\beta)}|H_j}^{(fc)}$ for $j = 0, 1$ based on Eq. (10)
    Compute $f_{Z^{(\beta)}|H_j}$ based on Eq. (14)
    $q \leftarrow 0$, $\tau^{(\beta)} \leftarrow L_q$
    while $p_d \geq p_d^{(t)}$ **do**
      for $P_D = 0 : \delta_D : P_D^{\max}$ **do**
        Compute η based on Eq. (18)
        if $\eta \geq \eta^{(t)}$ **then**
          Compute E based on Eq. (19)
          if $E < E_{\min}$ **then**
            $E_{\min} \leftarrow E$
            $\tau_*^{(\beta)} \leftarrow \tau^{(\beta)}, \beta_* \leftarrow \beta$
            $P_{R*}^{(fc)} \leftarrow P_R^{(fc)}, P_{D*} \leftarrow P_D$
          end if
        end if
      end for
      $q \leftarrow q + 1$, $\tau^{(\beta)} \leftarrow L_q$
    end while
  end for
end for

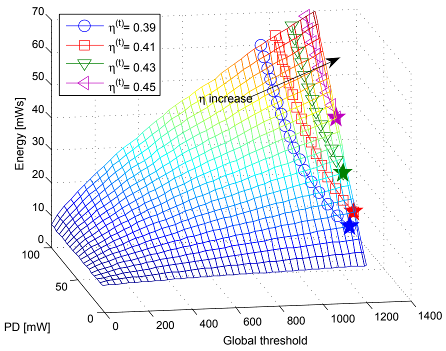

Figure 2. E versus P_D and $\tau^{(\beta)}$ when $\beta = 2$, and $P_R^{(fc)}$ = 10 mW

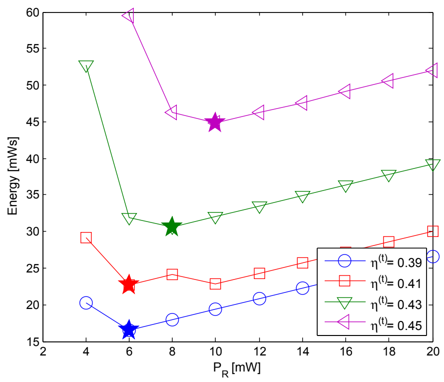

Figure 3. E versus $P_R^{(fc)}$ when $\beta = 2$, and P_D and $\tau^{(\beta)}$ chosen for minimizing the energy under **C2** and **C3**

while with low β the total energy for transmitting data must be high in order to satisfy **C2**.

In Fig. 5, the minimum of E is plotted with respect to $\eta^{(t)}$ for

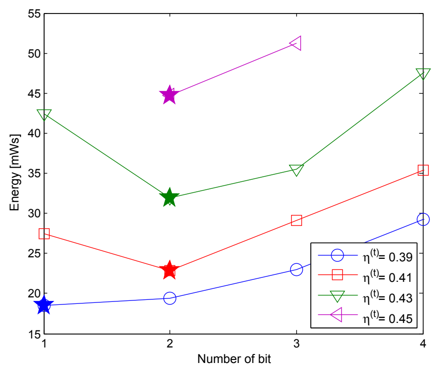

Figure 4. E versus β when $P_R = 10$ mW, and P_D and $\tau^{(\beta)}$ chosen for minimizing the energy under **C1**, **C2** and **C3**

three values of detection probability requirement. Increasing the requirement for protecting primary user or the requirement of throughput requires more energy. In particular, if these requirements are too strong, we may even not find operation point. Actually, for a certain $p_d^{(t)}$, the maximum achievable throughput is obtained as $\eta_{\max}^{(t)} = r(T_D^*/T)[\pi_0(1-p_f^*)+(1-\pi_0)(1-p_d^{(t)})]$ by putting $P_D = \infty$ and by selecting T_D^* and p_f^*

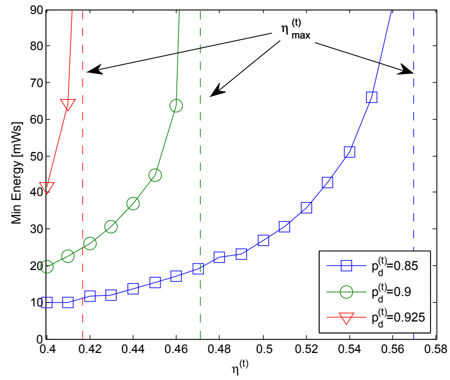

Figure 5. E versus $\eta^{(t)}$

corresponding to the best number of reported bits and the best threshold at $p_d = p_d^{(t)}$. Obviously, $\eta^{(t)}$ can not be considered larger than $\eta_{\max}^{(t)}$.

VI. Conclusion

We have minimized the consumed energy for cooperative sensing-based CR network while forcing minimum primary user protection and data rate with respect to some design parameters. Simulation results show that the gain is significant if design parameters are well-tuned.

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