On Results' Reporting of Cooperative Spectrum Sensing in Cognitive Radio Networks

Saud Althunibat and Fabrizio Granelli
University of Trento, DISI, Via Sommarive 14, I-38123, Trento, Italy
{althunibat, granelli}@disi.unitn.it

Abstract

One of the main challenges of cooperative spectrum sensing in cognitive radio networks is the overhead in terms of high energy consumption especially when reporting the individual sensing results to a common receiver. Such issue becomes more challenging for battery-powered users, because of its direct influence on achievable performance represented by detection accuracy. Thus, energy efficiency in cognitive radio networks has received a lot of attention during recent years. In this paper, we present a novel reporting scheme for spectrum sensing results, which significantly reduces the energy consumption without any effect on the detection accuracy. The proposed scheme allows the fusion center to terminate the reporting process whenever the received results are enough to make a decision according to the employed Fusion Rule (FR). Hence, the energy consumed in results' reporting is reduced as the number of reporting users is lower, and the data transmission can be started earlier, which enhances the achievable throughput. Moreover, the proposed scheme is consistent with many other energy-efficient approaches, leading to improve the energy efficiency achieved by these approaches. Mathematical expressions for the average number of reporting users for several FRs are obtained. Simulation and analytical results show a significant improvement in the energy efficiency.

Keywords: Cognitive Radio Networks; Specturm Sensing; Cooperative Specturm Sensing; Energy Efficiency.

I. Introduction

The new generations of wireless communications are expected to serve multiple users with diverse Quality-of-Services requirements. To fulfill these expectations, a huge amount of energy is required either at the base station or user-end. This represents a big challenge for wireless operators, not only because energy consumption constitutes a significant portion of running costs, but also because energy resources are limited, especially at the user-end. Therefore, energy efficiency in wireless communications systems has recently received increasing attention [1]. A system whose characteristics imply more energy consumption than legacy systems is Cognitive

Radio (CR). CR is actually a spectrum sharing process between licensed and unlicensed users. There are three defined CR models in the literature, namely, overlay, underlay and interweave [2], [3], [4]. In overlay and underlay models, the concurrent transmission from both sets of users is allowed. However, in underlay CR, the transmit power of the unlicensed users should be controlled in order to minimize the interference at the licensed users, while, in overlay model, the unlicensed user should act as relays for the licensed users by dedicating a part of their transmit power to retransmit the signal of licensed users. Unlike overlay and underlay models, interweave-CR bans the concurrent transmission. In interweave-CR, which is adopted in this paper, only the unused portions of a licensed spectrum can be exploited by unlicensed users. This requires awareness of spectrum status, which implies that a new task, termed as spectrum sensing, has to be performed before using the spectrum [5], [6].

In spectrum sensing, the unlicensed users, also called Cognitive Users (CUs), have to sense the target spectrum for a specific period, inducing additional energy consumption. Moreover, for high performance in spectrum sensing, the local sensing results are sent to a common receiver, called Fusion Center (FC), in order to process them according to a predefined Fusion Rule (FR), and issue a final decision about spectrum status, which is known as Cooperative Spectrum Sensing (CSS) [7], [8], [9], [10]. Two well-known schemes for results' reporting are available: soft-based scheme [11] , where the result of each user is quantized locally using usually a large number of bits, and conveyed to the FC, and hard-based scheme [12], where the result is quantized by only one bit and reported to the FC. Although CSS considerably decreases the probability of erroneous decision by mitigating the effects of multipath fading and shadowing, it causes extra delay, security risks [13] and higher energy consumption [14].

Several approaches have been presented in the literature in order to reduce energy consumption in CSS. In [15], the energy consumption is reduced by using the minimum number of CUs that guarantees a specific predefined detection accuracy. In [16] the CUs are divided in disjoint subsets, where each subset senses for a period of time while the other subsets are kept idle. In [17], a CU will participates in CSS only if its expected energy consumption is less than a threshold. The optimizing of the sensing time is exploited to reduce energy consumption in [18]. Optimizing the FR for maximizing energy efficiency is addressed under different setups and constraints in [19] [20] and [21]. Another popular approach is clustering approach [22], [23],

[24], where CUs are separated in clusters and only one CU from each cluster, called cluster-head, is in charge of processing the local results of the cluster-members. Cluster-head reports only one result on behalf of the whole cluster. The confidence voting scheme is proposed in [22] to reduce energy consumption in CSS. In confidence voting, if the results of a CU accord with the global decision, it gains confidence; otherwise, it loses confidence. If the confidence level falls below a predefined a threshold, the CU will not report its result, but it keeps sensing and tracking the final decision. Once its confidence level exceeds the threshold, it will rejoin the voting. In [25], a censoring scheme is presented, where the local sensing result is reported only if it is within a certain information region. Recently, in [26] and [27], a log-likelihood ratio based CSS scheme is proposed. It implies that each SU performs a local log-likelihood ratio based sensing test employing two threshold levels. The local decision and sequentially estimated SNR parameter values (for weight computation) are not reported to the FC if the local test result is in-between the two threshold levels. However, although the above presented approaches reduce energy consumption in CSS, they also degrade the detection accuracy, which negatively influences the energy efficiency of the whole cognitive transmission.

In this paper, a novel reporting scheme is proposed in order to reduce energy consumption in CSS without affecting the detection accuracy. The proposed scheme is based on the assumption that the results are reported to the FC consecutively in a TDMA scheme, which allows the FC to terminate the reporting process whenever the received results are enough to make a global decision according to the employed FR. In other words, while the users are reporting their results, the received results are being processed at the FC, and whenever the amount of information is enough to make a global decision based on the FR without need for additional notifications, a global decision is made and the reporting phase is terminated by broadcasting a message from the FC informing the CUs to stop the process.

Considering the definition of the energy efficiency as the average successfully transmitted bits over the average energy consumption, the properties of the proposed scheme are as follows; (i) The energy consumption reduction refers to preventing the rest of CUs, which wait their turn, from reporting, (ii) Since the reporting process will be terminated earlier, more time will be allocated to data transmission, which improves achievable throughput, and consequently, energy efficiency, (iii) The proposed scheme does not require/induce any energy consumption in preceding/following stages in the cognitive transmission, (iv) Most importantly, the proposed scheme does not affect the detection accuracy, and (v) The proposed scheme is consistent with most of the other energy-efficient CSS approaches presented in the literature, and can be jointly applied with any of them, which enhances the overall joint achievable energy efficiency.

The idea was initially presented in our work [28], where we investigate the proposed scheme in hard-based CSS with identical sensing performance among CUs. However, the contributions of this work over [28] can be summarized as follows: (i) The proposed scheme is applied to soft-based CSS in addition to hard-based CSS, (ii) The case of non-identical performance of the CUs is considered, (iii) The significance of the order of the CUs during reporting phase is investigated, and (iv) The consistency with other energy efficient approaches is discussed and proved through computer simulations.

The rest of this paper is organized as follows. Section II describes the system model, where the hard-based CSS and soft-based CSS are discussed, and the energy consumption analysis is explored. In Section III the proposed energy-efficient CSS scheme is presented along with its mathematical formulas related to hard and soft-based CSS. The consistency with other energy efficient approaches is shown in Section IV. Conclusions are drawn in Section V.

II. System Model

Consider a cognitive radio network (CRN) consisting of N CUs. All CUs try to use another spectrum without introducing extra interference to the licensed users of that spectrum, called Primary Users (PU). The probability that the spectrum is not being used by a PU is denoted by P_0. To avoid collision with PUs, each CU senses the target spectrum for a specific time, denoted as T_s. The optimal method for spectrum sensing is energy detection method [29] especially when no prior information is available about the PU signals. The received signal for any sample by the i^{th} CU is represented as follows

$$r_i(t) = \begin{cases} x(t) + n(t) & H_1 \\ n(t) & H_0 \end{cases} \tag{1}$$

where $x(t)$ is the PU transmitted signal and $n(t)$ is the complex additive white Gaussian noise with zero mean. Let us denote the signal to noise ration (SNR) of the i^{th} CU by γ_i. H_0 and H_1 represent the two hypotheses of absence and presence of the PU, respectively. The output of the energy detector, denoted as Y, is expressed as follows

$$Y_i = \sum_{s=1}^{S} \mid r_{i,s} \mid^2 \tag{2}$$

where $S = T_s f_s$, and f_s is the sampling frequency during sensing.

According to [8] and [30], Y_i follows a central chi-square (χ^2) distribution with $2S$ degrees of freedom under H_0 hypothesis, and non-central chi-square distribution with $2S$ degrees of freedom and a non centrality parameter $2S\gamma_i$ under H_1 hypothesis. Therefore, the probability density function (pdf) of Y_i is expressed as follows

$$f_{Y_i}(y) = \begin{cases} \frac{1}{2^S \Gamma(S)} y^{S-1} e^{-y/2} & H_0 \\ \frac{1}{2} \left(\frac{y}{2\gamma_i}\right)^{\frac{S-1}{2}} e^{-\frac{2\gamma_i + y}{2}} I_{S-1}(\sqrt{2\gamma_i y}) & H_1 \end{cases} \tag{3}$$

where $\Gamma(.)$ is the gamma function [31] and $I_v(.)$ is the v^{th} order modified Bessel function of the first kind [31].

A. *Cooperative Spectrum Sensing (CSS)*

As stated in the introduction, the individual spectrum sensing suffers of the poor performance due to the multipath fading and shadowing which can be mitigated by employing cooperation among CUs. CSS implies that CUs should cooperatively decide the final decision regarding the spectrum occupancy, which requires that all the individual sensing results are reported to the FC.

We assume that the local results are reported to the FC in different time slots based on a TDMA scheme [15]. Two popular schemes for reporting the local results are in the literature, Soft-based CSS and Hard-based CSS (both will be discussed in detail in this section). However, regardless the employed CSS scheme, two main metrics are used to evaluate the resulting detection accuracy, namely, detection probability and false-alarm probability. Detection probability is defined as the probability that the used spectrum will be correctly identified, whereas the false-alarm probability is the probability that the unused spectrum is incorrectly identified.

1) Soft-based Cooperative Spectrum Sensing (S-CSS): In S-CSS, CUs send their actual sensing information, i.e., Y's, to the FC without any local processing, and a global decision is made at the FC by combining them appropriately. The most popular combining scheme is the equal-gain combining (EGC) [32], where all the received results are summed up at the FC, as follows

$$Y_0 = \sum_{i=1}^{N} Y_i \tag{4}$$

Hence, the pdf of the statistic Y_0 follows the same distribution of Y_i, described in (3), with replacing each $2S$ by the product $2NS$, as follows [8] [30]

$$f_{Y_0}(y) = \begin{cases} \frac{1}{2^{NS}\Gamma(NS)} y^{NS-1} e^{-y/2} & H_0 \\ \frac{1}{2}\left(\frac{y}{2\gamma_0}\right)^{\frac{NS-1}{2}} e^{-\frac{2\gamma_0+y}{2}} I_{NS-1}(\sqrt{2\gamma_0 y}) & H_1 \end{cases} \tag{5}$$

where $\gamma_0 = \sum_{i=1}^{N} \gamma_i$.

The global decision is made by comparing the sum Y_0 with a predefined threshold λ_s. If $Y_0 \geq \lambda_s$, the spectrum will be declared as used. Otherwise, the spectrum will be identified as unused. The resulting detection probability and false-alarm probability are expressed as follows [8] [30]

$$P_D^{soft} = Q_{NS}(\sqrt{2\gamma_0}, \sqrt{\lambda_s}) \tag{6}$$

$$P_F^{soft} = \frac{\Gamma(NS, \lambda_s/2)}{\Gamma(NS)} \tag{7}$$

where $Q_{NS}(a, b)$ is the generalized Marcum Q-function [33].

2) Hard-based Cooperative Spectrum Sensing (H-CSS): In contrast to S-CSS, employing H-CSS implies that each CU processes its sensing result (Y_i) and issues a local binary decision $u_i\{1, 0\}$ about the spectrum status. If $Y_i \geq \lambda_{loc}$, then $u_i = 1$ (the spectrum is identified as used by the $i^t h$ CU). Otherwise, $u_i = 0$ (the spectrum is identified as unused by the i^{th} CU).

The detection accuracy of the local decision is also measured by local detection probability and local false alarm probability, which are given as follows [8]

$$P_{d,i}^{local} = Q_S(\sqrt{2\gamma_i}, \sqrt{\lambda_{loc}}) \tag{8}$$

$$P_{f,i}^{local} = \frac{\Gamma(S, \lambda_{loc}/2)}{\Gamma(S)} \tag{9}$$

According to H-CSS, all the obtained local decisions should be reported to the FC. At the FC, a specific fusion rule (FR) is employed to process these reported decisions in order to make a global decision. The general FR is *K-out-of-N* rule [34], where K is a predefined threshold on the number of CUs that detect a signal in the spectrum, i.e., the users that have obtained a local decision of 1, while N is the total number of CUs. The idea behind this rule is to compare the number of received 1's to K, where $1 \leq K \leq N$. If it is $\geq K$, then the spectrum is identified as used. Otherwise, the spectrum is identified as unused. The following equation describes the function of *K-out-of-N* rule:

$$Global\, decision = \begin{cases} used(1) & \text{if} \quad \sum_{i=1}^{N} u_i \geq K \\ unused(0) & \text{if} \quad \sum_{i=1}^{N} u_i < K \end{cases} \tag{10}$$

The overall detection probability and false alarm probability can be expressed in mathematical forms for arbitrary values of K as follows:

$$P_D^{hard} = \sum_{k=K}^{N} \sum_{j=1}^{\binom{N}{k}} \prod_{i \in A_j^{(N,k)}} P_{d,i} \prod_{i \notin A_j^{(N,k)}} \left(1 - P_{d,i}\right) \tag{11}$$

$$P_F^{hard} = \sum_{k=K}^{N} \sum_{j=1}^{\binom{N}{k}} \prod_{i \in A_j^{(N,k)}} P_{f,i} \prod_{i \notin A_j^{(N,k)}} \left(1 - P_{f,i}\right) \tag{12}$$

where $A_1^{(N,k)}, A_2^{(N,k)}, ..., A_{\binom{N}{k}}^{(N,k)}$ represent all the possible combinations of k integers drawn from the interval $[1, N]$, and the number of these combinations is $\binom{N}{k}$.

Depending on K, two popular FRs are derived from the *K-out-of-N* rule: OR rule ($K = 1$) and AND rule ($K = N$). The overall detection probability and false alarm probability for H-CSS based on OR rule are respectively given as follows

$$P_D^{or} = 1 - \prod_{i=1}^{N} \left(1 - P_{d,i}\right) \tag{13}$$

$$P_F^{or} = 1 - \prod_{i=1}^{N} \left(1 - P_{f,i}\right) \tag{14}$$

while for AND rule as follows

$$P_D^{and} = \prod_{i=1}^{N} P_{d,i} \tag{15}$$

$$P_F^{and} = \prod_{i=1}^{N} P_{f,i} \tag{16}$$

However, as a special case, when all CUs have identical sensing performance, i.e., $P_{d,i} = P_d \,\&\, P_{f,i} = P_f \;\forall i$, the overall detection and false-alarm probabilities are respectively given for any value of K as follows [19]

$$P_D^{hard} = \sum_{k=K}^{N} \binom{N}{k} P_d^k (1 - P_d)^{N-k} \tag{17}$$

$$P_F^{hard} = \sum_{k=K}^{N} \binom{N}{k} P_f^k (1 - P_f)^{N-k} \tag{18}$$

B. Energy Consumption in CSS

Fig.1 shows the frame structure of the cognitive transmission. At the beginning, all CUs sense the target spectrum for $T_s\,sec$ simultaneously. After that, all CUs report their local results consecutively in a specific order according to TDMA scheme, where each CU has its own reporting slot ($T_r\,sec$) for its result. The i^{th} CU remains in an idle state waiting its slot to report the local decision. After reporting the decision, the i^{th} CU returns back to the idle state until the global decision is made. The total length of time consumed in reporting all decisions equals to $NT_r\,sec$. The total length of time to wait associated to any CU equals to $(N-1)T_r\,sec$. After reporting all decisions, a global decision is made. If the global decision declares the spectrum as unused, then a CU is scheduled and starts data transmission for the rest of frame ($T_t\,sec$).

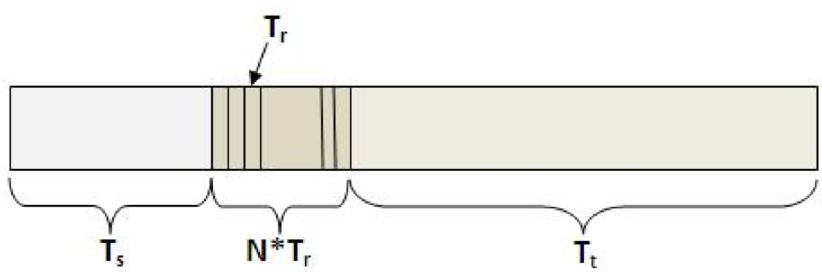

Fig. 1. *The frame structure of the cognitive transmission.*

According to the frame structure, a CU has four possible different states, namely, sensing state, idle state, reporting state and transmitting state. If we neglect the power consumed during idle state, and denote the power consumed by one CU during sensing, reporting and transmitting by α_s, α_r and α_t, respectively, the total energy consumed by N CUs is given as

$$E = N\alpha_s T_s + N\alpha_r T_r + P_t \alpha_t T_t \tag{19}$$

where P_t is the transmission probability expressed as follows

$$P_t = P_0(1 - P_F) + P_1(1 - P_D) \tag{20}$$

Another important quantity that should be defined is the amount of the successfully transmitted data (D) measured in bits. We assume that the successful transmission only occurs if the unused spectrum is correctly identified [15]. D is given as

$$D = P_0(1 - P_F)RT_t \tag{21}$$

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.

Finally, for the purpose of assessing the energy efficiency in $[bit/Joule]$, we define the the achievable energy efficiency (μ) as follows

$$\mu = \frac{D}{E} = \frac{P_0(1 - P_F)RT_t}{N\alpha_s T_s + N\alpha_r T_r + P_t\alpha_t T_t} \tag{22}$$

It is worthy mentioning that E, D and μ are different for each CSS scheme, S-CSS or H-CSS. Thus, while using (19)-(22), it should be noted that the values of T_r, T_t, P_D, P_F and P_t are different for each scheme.

III. Energy-Efficient Cooperative Spectrum Sensing (EE-CSS)

The energy consumed during CSS represents a challenge that degrades the overall energy efficiency of cognitive transmission. The energy consumed in results' reporting dominates the energy consumption in CSS. Therefore, reducing the number of CUs that report their results to the FC represents a preferred energy-efficient approach since it leads to a huge reduction in the consumed energy [10]. However, such approach should not negatively affect the achievable performance represented by the detection accuracy of CSS. In this section, we present a novel reporting scheme by which the total amount of energy consumed is reduced, the achievable detection accuracy is kept unaffected, the amount of transmitted data is increased, and hence, higher energy efficiency is achieved.

The idea behind our proposal is that while the CUs report their results, the FC should process these local results immediately, and whenever the FC can make a global decision from the received results, a message is sent from the FC to the rest of CUs, preventing them from reporting their local results. In other words, according to the adopted FR, in some cases, the FC can make the global decision without hearing from all the CUs, and hence, the reporting process should be stopped and the data transmission process can be commenced earlier. Accordingly, the number of reporting CUs decreases, which reduces the consumed energy, and the data transmission can be started earlier, achieving higher amount of transmitted data. Notice that the performance of the CSS represented by the detection accuracy is not affected.

Let us denote the number of the reporting CUs based on our proposal by M. In the rest of this section, we formulate the average number of reporting CUs based on the proposed technique in both S-CSS and H-CSS. Afterward, a discussion on the resultant energy consumption, detection accuracy, transmitted data and energy efficiency is presented.

A. Energy-Efficient S-CSS

In S-CSS, the global decision is made by comparing the sum of received results to a predefined threshold (λ_s). Thus, at a specific point during the reporting phase, if the sum of the received results up to that point is larger than λ_s, then the decision can be made without waiting the other results of the rest of CUs.

In view of this, the number of reporting CUs will be m if the sum of the results of the first $m-1$ reporting CUs is less than λ_s and the sum of the results of the first m reporting CUs is larger than or equal λ_s. Mathematically, the probability of the number of reporting CUs in S-CSS is expressed as follows:

$$Pr.\{M=m\} = \begin{cases} F^{(m-1)}(\lambda_s)\big(1-F^{(m)}(\lambda_s)\big) & 1 \le m < N \\ F^{(N-1)}(\lambda_s) & m = N \end{cases} \tag{23}$$

where $F^{(x)}(y)$ is the cumulative distribution function (CDF) of the sum of the sensing results for the first x reporting CUs. The pdf of $F^{(x)}(y)$, denoted by $f^{(x)}(y)$, is given as follows

$$f^{(x)}(y) = \begin{cases} \frac{1}{2^{xS}\Gamma(xS)} y^{xS-1} e^{-y/2} & H_0 \\ \frac{1}{2}\left(\frac{y}{2\gamma_x}\right)^{\frac{xS-1}{2}} e^{-\frac{2\gamma_x+y}{2}} I_{xS-1}(\sqrt{2\gamma_x y}) & H_1 \end{cases} \tag{24}$$

where $\gamma_x = \sum_{i=1}^{x} \gamma_i$ and $F^{(0)}(\cdot) = 1$.

The average number of reporting CUs ($\overline{M}^{soft}$) can be computed as follows

$$\overline{M}^{soft} = \sum_{m=1}^{N} mPr.\{M=m\} \tag{25}$$

by using (23), (25) can be rewritten as follows

$$\overline{M}^{soft} = NF^{(1:N-1)}(\lambda_s) + \sum_{m=1}^{N-1} mF^{(1:m-1)}(\lambda_s)\big(1-F^{(1:m)}(\lambda_s)\big) \tag{26}$$

The decrease in the number of reporting CUs will affect the system in two ways: first it decreases the total energy consumed in CSS, and it makes the data transmission, if any, starts earlier. The former effect reduces the total energy consumption, while the latter increases the achievable throughput. Thus, both result in improved energy efficiency. Let us define Energy Efficiency Ratio (EER) as the ratio of the achievable energy efficiency of the proposed EES-CSS to the achievable energy efficiency of the conventional S-CSS, as follows:

$$ERR = \frac{\mu'}{\mu} \tag{27}$$

where μ' is the achievable energy of the proposed approach, defined as follows:

$$\mu' = \frac{P_0\big(1 - P_F\big)R\bigg(T_t + (N - \overline{M})T_r\bigg)}{N\alpha_s T_s + \overline{M}\alpha_r T_r + P_t\bigg(T_t + (N - \overline{M})T_r\bigg)\alpha_t} \tag{28}$$

Compared to (22), in (28) the number of reporting CUs has been changed form N to $\overline{M}$ and the transmission time has been increased by $(N - \overline{M})T_r$.

Considering that all CUs have equal SNRs, the order of CUs during reporting phase does not affect the overall performance of the proposed scheme since all are identical at the FC side. In contrast, having CUs with non-equal SNRs implies that the reporting order has a significant influence on the achievable performance of the proposed scheme. Thus, the reporting order should be carefully designed in order to maximize the energy efficiency achieved by the proposed scheme.

Since the proposed scheme aims at terminating the reporting phase as fast as possible, then those CUs that are able to do so should report their results first. In S-CSS scheme, the global decision can be made earlier if the sum of the received results exceeds λ_s. Hence, the CUs should report their results to the FC according to a *descending* order of their average reported results, i.e., Y's.

Using (3), the average of Y_i can be expressed as follows

$$\overline{Y_i} = T_s F_s (2 + \gamma_i) \tag{29}$$

which implies that the optimal reporting order is equivalent to a *descending* order of the corresponding SNRs.

B. Energy-Efficient H-CSS

In H-CSS, the global decision can be made whenever the number of received 1's exceeds $K-1$ or the number of received 0's exceeds $N-K$. Accordingly, the probability of the number of reporting CUs follows the threshold K in the *K-out-of-N* FR, as follows

$$P\{M=m\}=\begin{cases} 0 & m<min\{K,N-K+1\} \\ P_{ad}+P_{af} & K\leq m<N-K+1 \\ P_{cd}+P_{cf} & N-K+1\leq m<K \\ P_{ad}+P_{cd}+P_{af}+P_{cf} & max\{N-K+1,K\}\leq m<N \\ \frac{P_{ad}}{P_{d,N}}+\frac{P_{af}}{P_{f,N}} & m=N \end{cases} \tag{30}$$

where

$$P_{ad}=P_1P_{d,m}\sum_{j=1}^{\binom{m-1}{K-1}}\prod_{i\in A_j^{(m-1,K-1)}}P_{d,i}\prod_{i\notin A_j^{(m-1,K-1)}}\left(1-P_{d,i}\right) \tag{31}$$

$$P_{af}=P_0P_{f,m}\sum_{j=1}^{\binom{m-1}{K-1}}\prod_{i\in A_j^{(m-1,K-1)}}P_{f,i}\prod_{i\notin A_j^{(m-1,K-1)}}\left(1-P_{f,i}\right) \tag{32}$$

$$P_{cd}=P_1\left(1-P_{d,m}\right)\sum_{j=1}^{\binom{m-1}{N-K}}\prod_{i\notin A_j^{(m-1,N-K)}}P_{d,i}\prod_{i\in A_j^{(m-1,N-K)}}\left(1-P_{d,i}\right) \tag{33}$$

$$P_{cf}=P_0\left(1-P_{f,m}\right)\sum_{j=1}^{\binom{m-1}{N-K}}\prod_{i\notin A_j^{(m-1,N-K)}}P_{f,i}\prod_{i\in A_j^{(m-1,N-K)}}\left(1-P_{f,i}\right) \tag{34}$$

where $A_1^{(x,y)},A_2^{(x,y)},...,A_{\binom{x}{y}}^{(x,y)}$ represent all the possible combinations of y integers drawn from the interval $[1,x]$.

As a special case, when all CUs have identical performance, (31)-(34) can be rewritten as follows:

$$P_{ad}=P_1\binom{m-1}{K-1}P_d^K(1-P_d)^{m-K} \tag{35}$$

$$P_{af}=P_0\binom{m-1}{K-1}P_f^K(1-P_f)^{m-K} \tag{36}$$

$$P_{cd}=P_1\binom{m-1}{N-K}P_d^{m-N+K-1}(1-P_d)^{N-K+1} \tag{37}$$

$$P_{cf} = P_0 \binom{m-1}{N-K} P_f^{m-N+K-1} (1-P_f)^{N-K+1} \tag{38}$$

In the following, we obtain the average number of reporting CUs according to the proposed technique for the two popular rules derived from *K-out-of-N* rule, OR rule and AND rule, when all CUs have identical sensing performance:

1) OR rule: In OR rule, $K = 1$, which means the global decision will be "$used$" if at least one CU reports "1". Eqn. (30) can be simplified in the case of OR rule by substituting $K = 1$ as follows

$$Prob.\{M^{or} = m\} = \begin{cases} P_{ad} + P_{af} & 1 \leq m < N \\ \frac{P_{ad}}{P_d} + \frac{P_{af}}{P_f} & m = N \end{cases} \tag{39}$$

The average number of reporting CUs in OR rule, denoted by $\overline{M}^{OR}$, can be derived after some algebra from (39), and is given as

$$\overline{M}^{or} = \frac{P_1 P_D^{or}}{P_d} + \frac{P_0 P_F^{or}}{P_f} \tag{40}$$

where P_D^{or} and P_F^{or} are given in (13) and (14), respectively.

2) AND rule: AND rule is another rule derived from the general *K-out-of-N* rule by substituting $K = N$, which means the global decision will be "$used$" only when all CUs report "1". Eqn. (30) can be simplified in the case of AND rule as follows

$$Prob.\{M^{and} = m\} = \begin{cases} P_{cd} + P_{cf} & 1 \leq m < N \\ \frac{P_{ad}}{P_d} + \frac{P_{af}}{P_f} & m = N \end{cases} \tag{41}$$

By the same way, we can write the average number of the reporting CUs based on our proposal for the AND rule ($\overline{M}^{and}$) as follows

$$\overline{M}^{and} = \frac{P_1(1-P_D^{and})}{1-P_d} + \frac{P_0(1-P_F^{and})}{1-P_f} \tag{42}$$

where P_D^{and} and P_F^{and} are given in (15) and (16), respectively.

IV. Simulation Results

In this section we present some simulation results that prove the high performance of the proposed schemes. Specifically, the performance of the proposed schemes is shown in terms of the average number of reporting users, and the EER with respect to the conventional scheme.

The number of the CUs is assumed 10 CUs, and the other parameters are listed in Table I. We start by showing the results of EES-CSS, and EEH-CSS, and a separate subsection is dedicated to show the consistency of the proposed scheme with other available schemes.

Table I: Simulation Parameters

Parameter	Value
P_0	0.5
F_s	$10^5\,Hz$
T	$30\,msec$
T_s	$1\,msec$
$T_r(soft)$	$0.8\,msec$
$T_r(hard)$	$0.1\,msec$
T_t	$T - NT_r - T_s$
α_s	$10\,mW$
α_t	$100\,mW$
α_r	$100\,mW$
R	$100\,Kbps$

Fig. 2 shows the average number of reporting CUs of the proposed EES-CSS versus the global decision threshold for different numbers of the available CUs. All CUs are assumed to be identical $\overline{\gamma} = 10$. Clearly, the proposed scheme uses an average number of reporting CUs that is lower than the number of reporting users in the conventional S-CSS, and it increases as the global decision threshold (λ_s) increases.

In Fig. 3 the EER of the proposed EES-CSS is shown versus the global decision threshold for different number of the available CUs. The improvement in the energy efficiency is notable and significant due to the reasons we have discussed earlier. It is worthy mentioning that the detection accuracy is not affected by the proposed scheme.

Fig. 4 and Fig. 5 show the average number of reporting CUs and EER of the optimal order (descending in SNRs) and the worst order (ascending in SNRs) versus the global decision threshold. 10 CUs are considered with SNR set $\gamma_{i=1}^{10} = \{1, 2, 3, 4, ..., 10\}$. A significant gain can be noted between the optimal order and the worst word represented by the average number of reporting CUs, see Fig.4, which results in a higher energy efficiency, see Fig. 5.

Fig. 6 plots the average number of reporting CUs according to the proposed EEH-CSS versus the global decision threshold (K) for different numbers of the available CUs. Unlike the curve

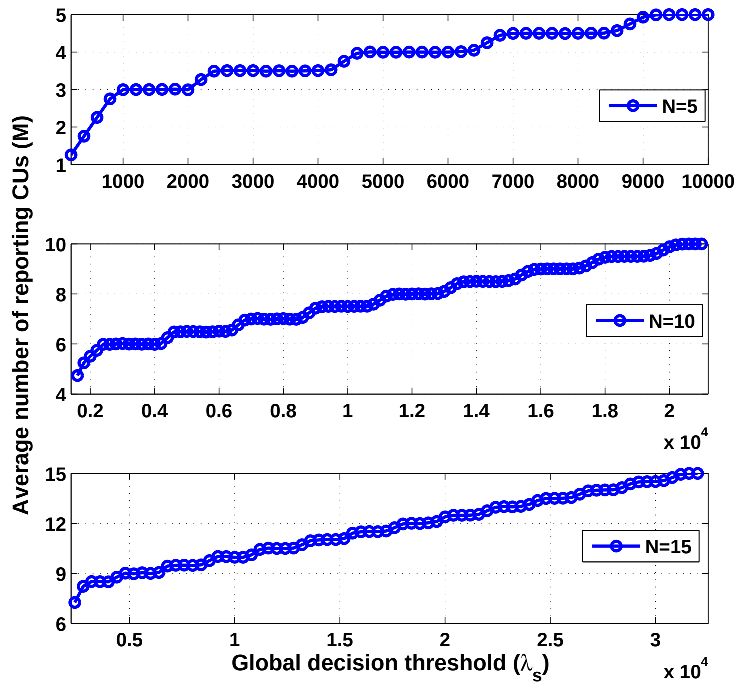

Fig. 2. *The average number of reporting CUs versus the global decision threshold in the proposed Soft-based CSS for different numbers of CUs. All CUs have* $\overline{\gamma} = 10$

of EES-CSS in Fig. 2, the average number of reporting CUs shows a concave curve in terms of the decision threshold. This is due to the fact that in S-CSS the global decision can made earlier only if the sum of the received results is larger than a threshold, while in H-CSS the global decision can be issued earlier in two cases: i) if the number of received 1's is equal to K, or ii) if the number of the received 0's exceeds $N - K$. Thus, for low values of K, the reporting phase is early terminated due to the high probability of receiving K 1's, whereas for high values of K, the high probability of receiving $N - K + 1$ 0's causes the early termination of the reporting phase.

The decrease in the average number of reporting CUs, shown in Fig. 6, is reflected on the energy efficiency ratio of the proposed EEH-CSS to the conventional H-CSS as shown in Fig. 7. Notice that the curves do not take the same behavior that was followed in Fig. 6, i.e., concave shape, because of that although high values of K achieve low number of reporting CUs, the increase in P_t alleviate the resulting effect on the energy efficiency. The same parameters listed in Table I have been used except T_r which has been set to $0.1\,msec$. The local decision threshold

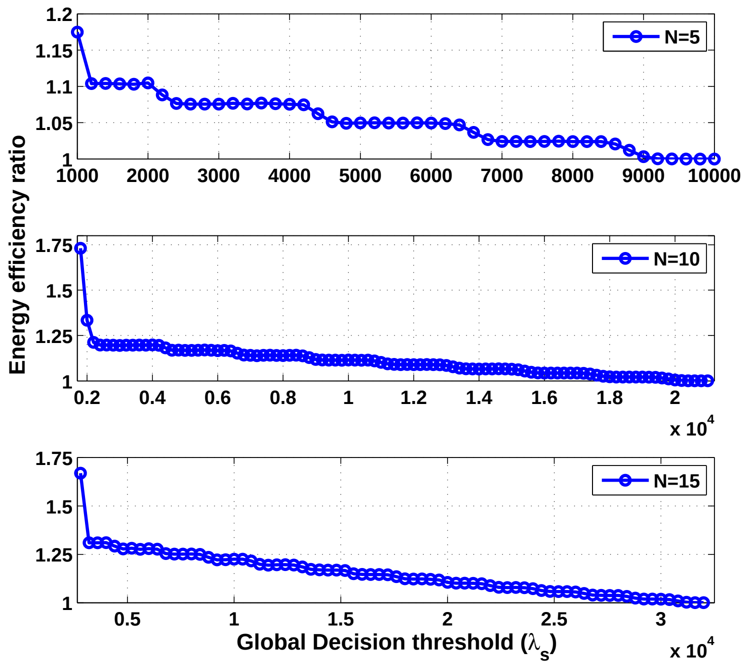

Fig. 3. *The ratio of the achievable energy efficiency of the proposed S-CSS to the achievable energy efficiency of the conventional S-CSS versus the global decision threshold for different numbers of CUs. All CUs have* $\overline{\gamma} = 10$

(λ_{loc}) has been set so that the resulting local false-alarm probability is $P_{f,i} = 0.3$.

Similar to the proposed EES-CSS, in case of non-equal SNRs among CUs, the reporting order has a significant effect on the improvement of the overall performance of the proposed EEH-CSS scheme. A CRN of 10 CUs with the average SNRs $\gamma_{i=1}^{10} = \{0.03, 0.06, 0.09, ..., 0.3\}$. The local false-alarm probability is set to 0.3 for all CUs by controlling λ_{loc} as in (9), while the corresponding local detection probability for each CU is obtained using (8). Fig. 8 shows the average number of reporting CUs versus K for two different orders in the reporting phase; *ascending* order and *descending* order of the SNRs. Apparently, there is a significant difference in the average number of reporting CUs between the two orders. However, identifying the optimal order depends on K and the SNRs of the CUs. Fig. 9 shows the resulting EER for the considered CRN according to the different orders.

A. Consistency with Other Approaches

An interesting property of the proposed scheme is that it can be jointly applied with many other approaches for energy efficient CSS, enabling to improve the achievable energy efficiency

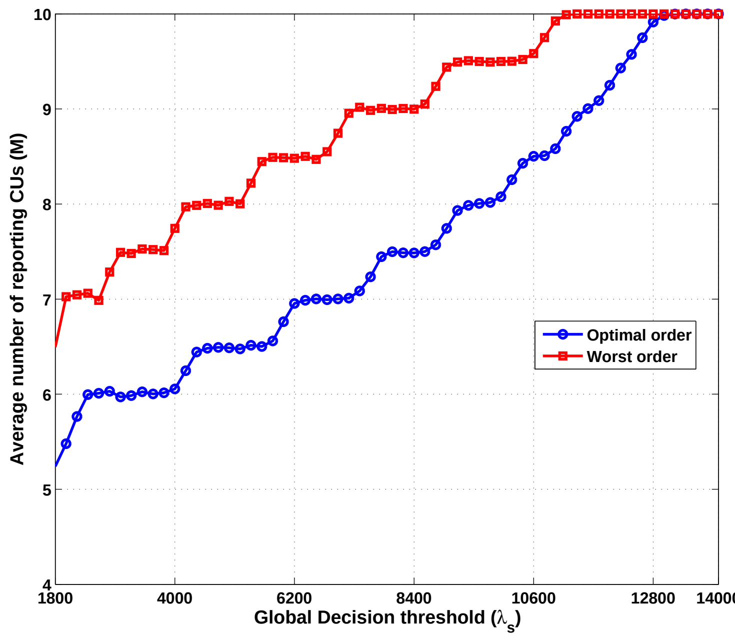

Fig. 4. *The average number of reporting CUs versus the global decision threshold in the proposed Soft-based CSS for the optimal oder and the worst order.* $N = 10$ *and* $\gamma_{i=1}^{10} = \{1, 2, 3, ..., 10\}$

of such approaches without any effect on their detection accuracy. Such approaches include most of the proposed energy efficient CSS proposed in the literature, such as cluster-based CSS [22] [23], dynamic-head cluster-based CSS [35], confidence-voting scheme [22], censoring scheme [25], minimizing the number of participating CU in CSS [15] [16] [18], and optimizing the sensing time [18] or the fusion rule [19]. In this section, we prove the consistency of the proposed approach with only the energy-efficient cluster-based CSS approach as an example.

Cluster-based cooperative spectrum sensing method was proposed to improve the sensing performance [36]. By separating all CUs into a few clusters and selecting the most favorable user in each cluster, named cluster-head, to report to the FC, the proposed method can exploit the user selection diversity so that the sensing performance can be enhanced. Moreover, clustering technique is adopted to save energy consumed in reporting results, where each cluster-head processes the local decisions of its cluster-members and reports only one local decision to the FC in behalf of the whole cluster [22] [23].

The reader can notice that the proposed scheme is consistent with the cluster-based approach, and both can be applied together without affecting the detection accuracy of the network. The

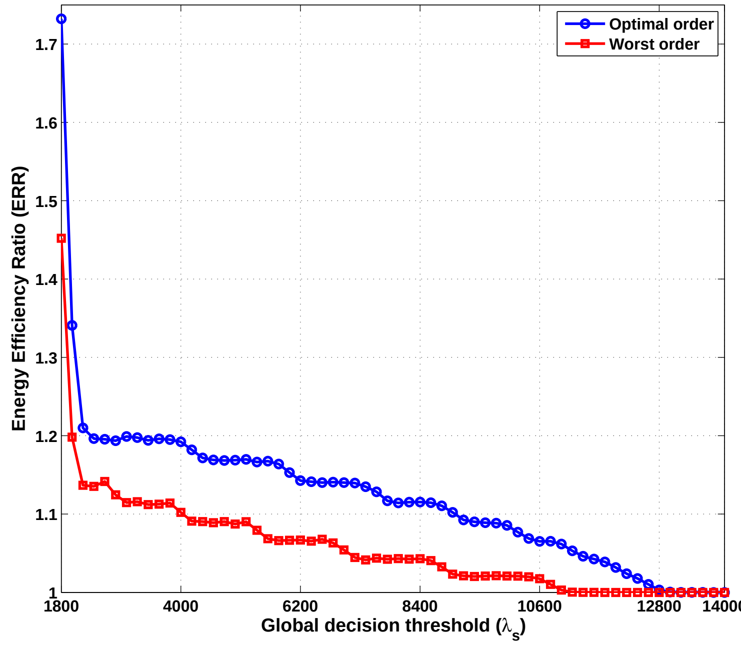

Fig. 5. *The ratio of the achievable energy efficiency of the proposed S-CSS to the achievable energy efficiency of the conventional S-CSS versus the global decision threshold for the optimal order and the worst order.* $N = 10$ *and* $\gamma_{i=1}^{10} = \{1, 2, 3, ..., 10\}$

proposed scheme can be applied in both the reporting phase between the cluster-members and cluster-head, and the reporting phase between the cluster-heads and the FC.

For comparison, we consider 50 CUs are clustered into 10 clusters, each cluster contains 5 CUs. The members of each cluster report their local decisions to the cluster-head. The cluster-head makes a cluster-decision based on the majority decision. The cluster-decisions will be forwarded to the FC consecutively based on a TDMA scheme. Finally, the FC will make the final decision based on the employed fusion rule. The local threshold for each CUs λ_{loc} is set so that $P_{f,i} = 0.3$, and the power consumed in reporting the local decision between a cluster-member and a cluster-head is considered $50\,mW$. The other parameters are in Table I.

Fig. 10 shows the achievable energy efficiency versus the overall false-alarm probability of the cluster-based CSS, the proposed approach and the conventional H-CSS. As an example, at $P_F = 0.1$, the cluster-based approach can improve the energy efficiency by 15% compared to the conventional H-CSS, while the proposed scheme achieves 11% improvement. However, since our proposal is consistent with the cluster-based approach, both can be applied together and an improvement up to 20% can be attained, as shown in Fig. 10.

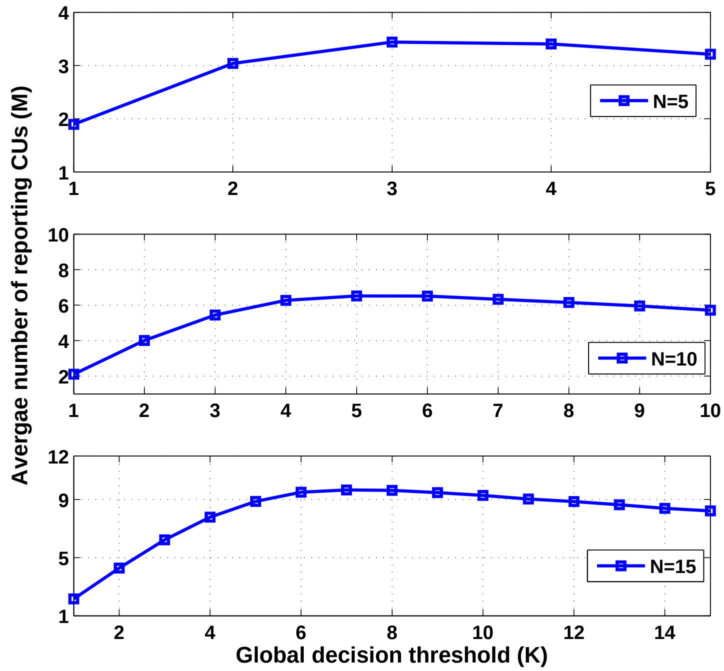

Fig. 6. *The average number of reporting CUs versus the global decision threshold in the proposed Hard-based CSS for different numbers of CUs. All CUs have* $\overline{\gamma} = 10$

V. CONCLUSIONS

The problem of improving the energy efficiency of cooperative spectrum sensing in cognitive radio networks by reducing the energy consumption in results' reporting phase is investigated in this paper, where a novel energy-efficient reporting scheme is presented in this work. The idea of the proposed scheme is based on terminating the reporting phase whenever the final decision can be made and exploiting the remainder time for data transmission. The most interesting property of the proposed scheme is that it does not affect the detection accuracy. Moreover, the proposed scheme can be jointly applied with many other energy efficient proposals, enhancing their achievable energy efficiency. Analytical and simulation results show a considerable improvement in the energy efficiency, thus demonstrating the good potential of the proposed strategy.

ACKNOWLEDGMENTS

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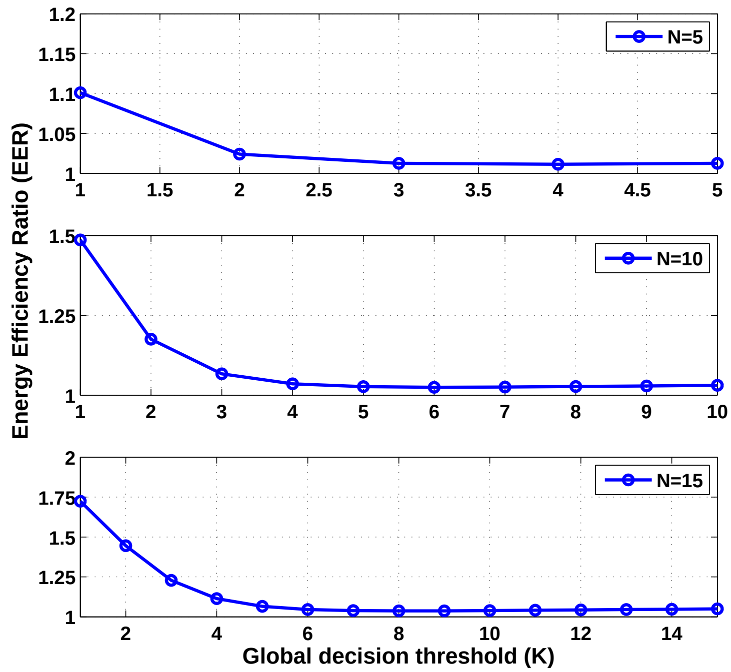

Fig. 7. *The ratio of the achievable energy efficiency of the proposed Hard-based CSS to the achievable energy efficiency of the conventional Hard-CSS versus the global decision threshold for different numbers of CUs. All CUs have* $\overline{\gamma} = 10$

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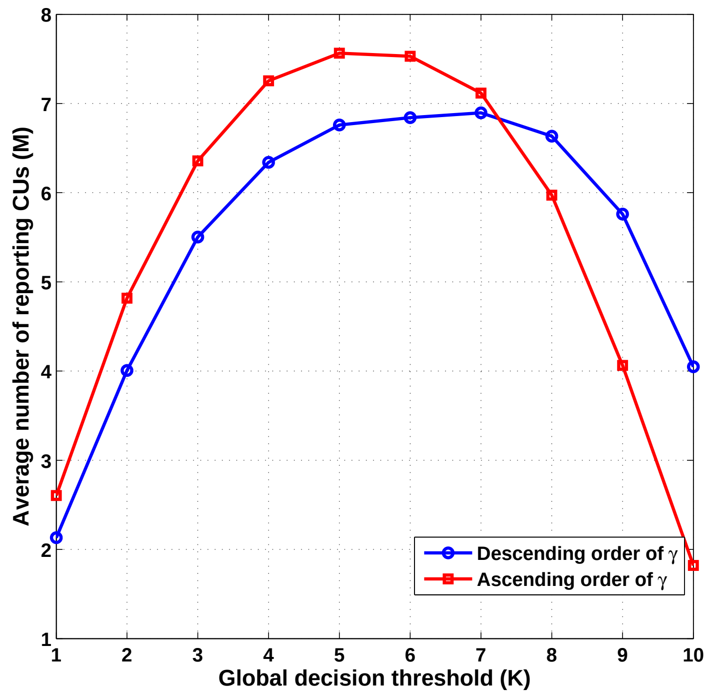

Fig. 8. *The average number of reporting CUs versus the global decision threshold in the proposed Hard-based CSS for the ascending oder and the descending order.* $N = 10$ *and* $\gamma_{i=1}^{10} = \{0.03, 0.06, 0.09, ..., 0.3\}$

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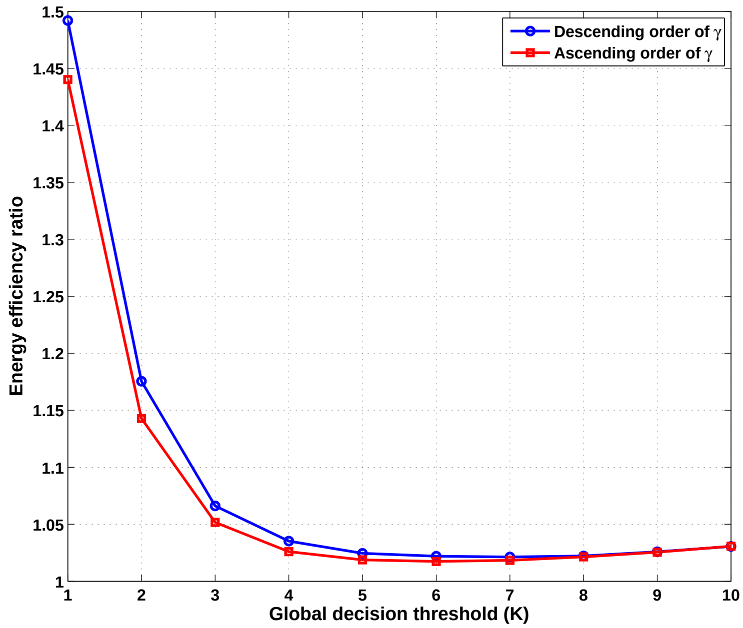

Fig. 9. *The ratio of the achievable energy efficiency of the proposed Hard-based CSS to the achievable energy efficiency of the conventional Hard-CSS versus the global decision threshold for the ascending oder and the descending order.* $N = 10$ *and* $\gamma_{i=1}^{10} = \{0.03, 0.06, 0.09, ..., 0.3\}$

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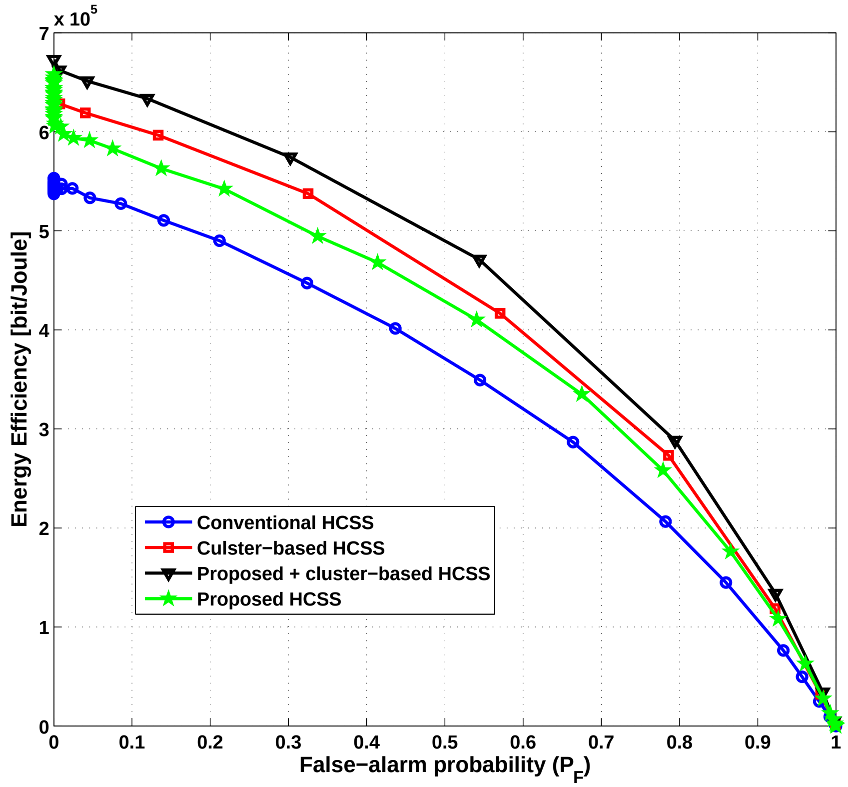

Fig. 10. *The achievable energy efficiency versus the global false-alarm probability (P_F) for the compared approaches. All CUs have* $\overline{\gamma} = 10$

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