Throughput Optimization for Cooperative Spectrum Sensing in Cognitive Radio Networks

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Abstract— **In this paper, the channel utilization (throughput vs sensing time relationship) is analyzed for cooperative spectrum sensing under different combining rules and scenarios. The combining rules considered in this study are the OR hard combining rule, AND the hard combining rule, the Equal Gain Soft combining rule and the two-bit quantized (softened hard) combining rule. For all combining rules, the detection performance, with a Gaussian distribution assumption, is expressed in two different scenarios, CPUP (Constant Primary User Protection) and CSUSU (Constant Secondary User Spectrum Usability). A comparison, based on simulations, is conducted between these proposed schemes in both scenarios, in terms of detection performance and throughput capacity of the CR network.**

Keywords-Cognitive Radio; Cooperative Spectrum Sensing; Capacity; Combining Rules;

I. INTRODUCTION

Cognitive Radio (CR) has been proposed to solve the conflicts between spectrum scarcity and spectrum underutilization [1]. CR users are allowed to utilize the spectrum resources when the PUs do not use the spectrum without causing harmful interference to PUs services. One of the issues in CR system is how the CR users detect the PUs whether they are present or absent. This task is known as Spectrum Sensing (SS) [2].

Several SS techniques are proposed and the most popular sensing techniques are: Energy Detection (ED), Cyclostationary feature detection, and matched filter detection [3]. ED is a well known detection method mainly because of its simplicity and it doesn't require any prior knowledge of the PU signal compared to other techniques.

Due to many factors such as multipath fading, shadowing and the noise uncertainty problem [2], the detection performance in SS can be degraded. To combat these impacts, Cooperative Spectrum Sensing (CSS) schemes have been proposed [4, 5].

In CSS, two or more CR users are organized to sense the licensed channel and report their sensing information to a fusion center (FC) through a dedicated control channel to make a more accurate decision. The sensing results can be combined in three different ways: hard combining rules, soft combining rules, and quantized (softened hard) combining rules. In the hard combining rule (OR, AND, and MAJORITY logic), CR users sense the PU individually and send their sensing observation in the form of 1-bit binary decisions (1 or 0) to the FC [4] [6] to make the final decision regarding whether the PU is present or not. The comparison between hard combining rules for cooperative spectrum sensing has been investigated in [6], and the k out of N rule for data fusion at the FC is proposed in [7]. In soft combining rules, CR users transmit the entire local sensing results to the FC, without taking a local decision. At the FC, existing receiver diversity techniques such as equal gain combining (EGC) rule and maximal ratio combining (MRC) rule can be utilized for soft combining [8]. These soft combining rules have shown better detection performance than the hard combining rules [9] however they require an overhead in terms of reporting channel bandwidth. In [10] a simulation comparison of soft and hard combining rules for cooperative sensing is presented concluding that the Likelihood Ratio Test (LRT) and soft optimal linear combining rules outperform the OR, equal weight combining, Majority and AND hard combining counting rules.

In [11], a quantized combining rule has been introduced as a tradeoff between soft and hard combining rules. In that paper, a two-bit combining rule is proposed in which each CR user reports the quantized two-bit information of its local test statistics to the FC.

Through the mechanism of spectrum sensing, we aim to get the optimal sensing time, in order to maximize the user data throughput of the CR network. The optimum capacity throughput of the CR users according with the requirements about the sensing accuracy must be searched. In [7], the CR users' network throughput is maximized subject to adequate protection provided to PUs by determining the optimal k-out-of-N combining rule. The sensing-throughput relationship is also analyzed. In [12], optimal multi-channel cooperative sensing algorithms are considered to maximize the CR users' network throughput subject to per channel detection probability constraints. The problem is solved by an iterative algorithm. In [13] the optimal sensing duration is studied to maximize the achievable throughput for the secondary network, assuming the local sensing results arrived at the common receiver in a TDMA protocol. In [14], the performance of CSS has been analyzed under two different operational modes, namely, CPUP (Constant Primary User Protection) and CSUSU (Constant Secondary User Spectrum Usability) when studying the capacity optimization under hard combining rules.

Our main contributions in this paper can be summarized as follows:

- Based on [11,14], we derive the overall detection performances in terms of probability of detection, and probability of false alarm under CPUP and CSUSU scenarios for the EGC soft combining rule and the two-bit quantized combining rule using Gaussian distribution approximations.
- In contrast to [14] that restrict the study of the throughput optimization under hard combining rules, we extend this study under soft combination rule based on EGC and for a quantized combination rule based on two bit hard combining.

The paper is organized as follows. In section II, we define the system model for the cognitive radio network that is used in analysis and simulations and we give more details on the CPUP and CSUSU scenarios. Section III presents the CSS using hard, soft and two-bit combining rules under both CPUP and CSUSU scenarios. The throughput optimization problem is studied for the different combining rules under CPUP and CSUSU scenarios in section IV; Simulation results and discussions are shown in section V. Section VI concludes this work.

II. System Model

Consider a cognitive radio network, with K cognitive users (indexed by $k = \{1, 2. . . K\}$) to sense the spectrum in order to detect the existence of the PU. Suppose that each CR performs local spectrum sensing independently by using N samples of the received signal. All cooperating CR users report their sensing results (u_1, u_2… u_K) via the control channel. Then the FC fuses the received local sensing information to make a final decision U whether the PU is present or not as shown in Fig.1. The spectrum sensing problem can be formulated as a binary hypothesis testing problem with two possible hypotheses H_0 and H_1.

$$\begin{aligned} H_0 &: x_k(n) = w_k(n) \\ H_1 &: x_k(n) = h_k s(n) + w_k(n) \end{aligned}, \tag{1}$$

where $s(n)$ are the samples of the transmitted signal from the PU, which are assumed to be a random process with variance σ_s^2, $w_k(n)$ is the receiver noise for the k^{th} CR user, which is assumed to be an i.i.d. random process with zero mean and variance σ_w^2 and h_k is the complex gain of the channel between the PU and the k^{th} CR user. H_0 and H_1 represent whether the signal is absent or present respectively.

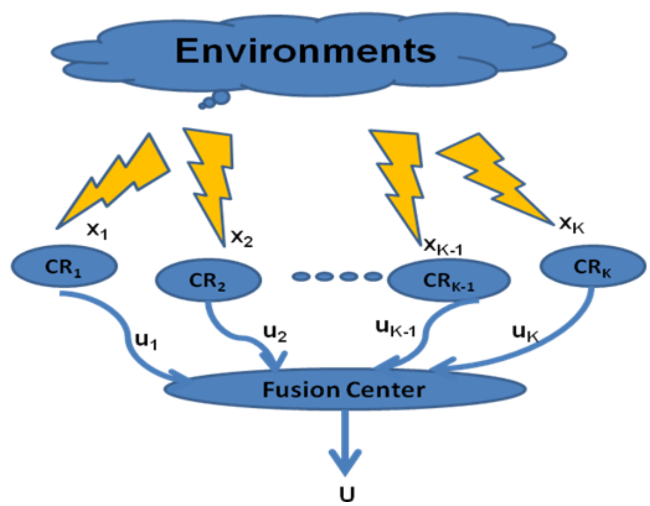

Fig. 1 Scheme of Cooperative Spectrum Sensing

A. *Decision statistical model for energy detection*

To be in line with [11, 14], the energy detector (ED) is used as a method for spectrum sensing. The advantage of ED is its low computational and implementation complexities. Based on ED, the k^{th} CR user will calculate the received energy as [15]:

$$E_k = \sum_{n=1}^{N} x_k^2(n) \ . \tag{2}$$

Hence, the energy detector performance can be given in terms of Probability of False Alarm and the Probability of Detection by:

$$\begin{aligned} P_{f,k} &= \Pr(E_k > \lambda_k / H_0) \\ P_{d,k} &= \Pr(E_k > \lambda_k / H_1) \end{aligned}, \tag{3}$$

where E_k is the test statistic and λ_k is the corresponding test threshold. Although E_k has a chi-square distribution, according to the central limit theorem, E_k is asymptotically normally distributed if N is a large enough. In this case, we can model the statistics of E_k as a Gaussian distribution with mean ($N\sigma_w^2$) and variance ($2N\sigma_w^4$) under hypothesis H_0, and as Gaussian distribution with mean ($N(\sigma_w^2+\sigma_s^2)$) and variance ($2N(\sigma_w^2+\sigma_s^2)^2$) under hypothesis H_1.

In this way, for large N (long sensing time), the Probability of False Alarm and the Probability of Detection, can be approximated, respectively, as [14]:

$$P_{f,k} = Q(\frac{\lambda_k - N\sigma_w^2}{\sqrt{2N\sigma_w^4}}), \quad (4)$$

$$P_{d,k} = Q(\frac{\lambda_k - N(\sigma_w^2+\sigma_s^2)}{\sqrt{2N(\sigma_w^2+\sigma_w^2)^2}}) \ . \quad (5)$$

B. Cognitive Radio Transmission Scenarios

In this paper, the sensing performance of a CR and a CR network is evaluated under two different operational modes, CPUP (Constant Primary User Protection) and CSUSU (Constant Secondary User Spectrum Usability) transmission modes. The CPUP mode guarantees a minimum level of interference to the PU. To realize this scenario, we fix the probability of detection at the required level and try to find a tradeoff between the probability of false alarm and the sensing time at a particular SNR. The CSUSU scenario is taken from the CR's perspective; by keeping fixed the usability of unoccupied bands at a certain level, in other term, we fix the Probability of false alarm at lower values and try to find the tradeoff between the probability of detection and the sensing time at a particular SNR.

Under CPUP, we can express P_f in terms of $\overline{P_d}$ and N as [14]

$$P_f = Q(Q^{-1}(\overline{P_d})(1+SNR) + SNR\sqrt{\frac{N}{2}}) \ , \quad (6)$$

where $\overline{P_d}$ is the required probability of detection under CPUP and $SNR=\sigma_s^2/\sigma_w^2$ is the signal to noise ratio of the PU signal at the CR.

Under CSUSU, we can express P_d in terms of $\overline{P_f}$ and N as [14]:

$$P_d = Q(\frac{Q^{-1}(\overline{P_f}) - SNR\sqrt{\frac{N}{2}}}{(1+SNR)}) \ , \quad (7)$$

where $\overline{P_f}$ is the required probability of false alarm under CSUSU.

In Fig. 2, we analyze the behavior of the probability of false alarm as a function of the sensing time for one user and constant SNR of -18 dB. We notice that for the same sensing time (same N), increasing the PU's protection level (by increasing the required probability of detection) leads to increase the probability of false alarm, thus, less chance for the CR users to utilize the channel. In Fig. 3, we plot the behavior of the probability of detection as a function of the sensing time; it is shown that for the same sensing time, increasing the spectrum usability (i.e decreasing the probability of false alarm) leads to decrease the protection of PU (Pd).

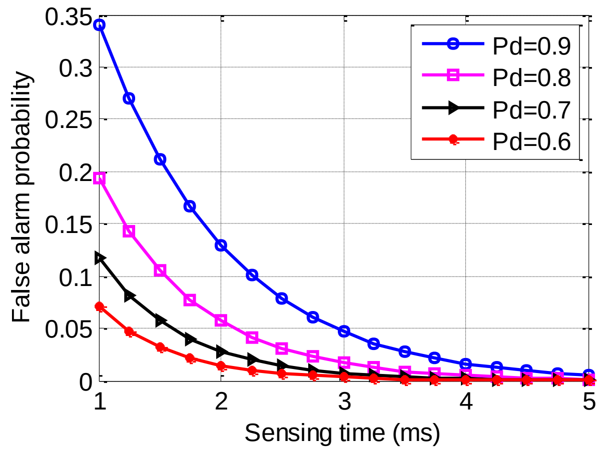

Fig. 2 Probability of false alarm versus sensing time (CPUP)

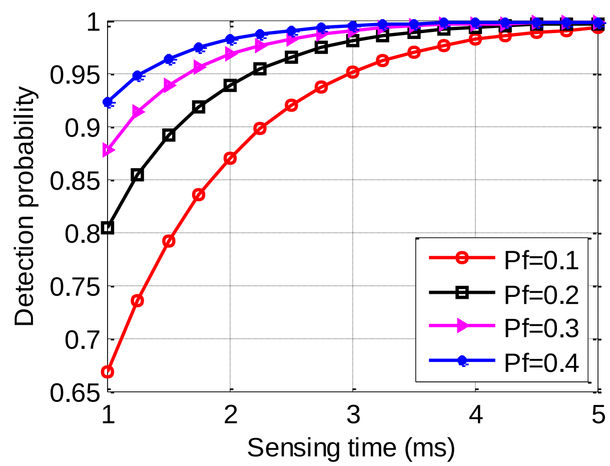

Fig. 3 Probability of detection versus sensing time (CSUSU)

III. COMBINING RULES FOR COOPERATIVE SPECTRUM SENSING

The CSS aims to improve detection sensitivity, especially when working under low signal to noise ratio (such as the SNR level proposed by 802.22 working group, which is -22 dB [16]).

In the following subsections, we will study three different combining rules for CSS: hard combining rule (OR and AND rule), soft combining rule (Equal Gain combining rule) and quantized combining rule (two-bit quantized combining rule). For each combining rule, we will express the CR network probability of false alarm Q_f in terms of the required overall probability of detection $\overline{Q_d}$ and N under CPUP scenario. We will also formulate the CR network probability of detection Q_d in terms of the required overall probability of false alarm $\overline{Q_f}$ and N under CSUSU scenario.

A. Hard Combining Rule

In this rule, each user decides on the presence or absence of the primary user and sends a one bit decision to the data fusion center. The main advantage of this method is the easiness and the fact that it needs limited bandwidth for the reporting channel [11].

In this subsection, considering both OR and AND combining rules, we analyze the performance of combining rules for CSS under CPUP and CSUSU scenarios.

The **AND** rule decides that a signal is present if ***all*** SUs have detected a signal. The CR network probability of false alarm Q_f, and the CR network probability of detection Q_d using the AND rule can be formulated as follows [4]:

$$Q_f = \prod_{k=1}^{K} P_{f,k} \ , \tag{8}$$

$$Q_d = \prod_{k=1}^{K} P_{d,k} \ . \tag{9}$$

The **OR** rule decides that a signal is present if ***any*** of the CR users detect a signal. Hence, the CR users' network probabilities using the OR rule can be expressed as follows:

$$Q_f = 1 - \prod_{k=1}^{K} (1 - P_{f,k}) \ , \tag{10}$$

$$Q_d = 1 - \prod_{k=1}^{K} (1 - P_{d,k}) \ . \tag{11}$$

The CR users' network probabilities can be stated under CPUP and CSUSU scenarios. The overall probabilities under **CPUP** scenario where the probability of detection is fixed at a satisfactory level $\overline{Q_d}$, can be expressed as [14]

Under OR rule

$$Q_f = 1 - \prod_{k=1}^{K} \left(1 - Q\left(\frac{(Q^{-1}(1-(1-\overline{Q_d})^{\frac{1}{K}})}{(1+SNR_k) + SNR_k\sqrt{\frac{N}{2}})} \right) \right) . \tag{12}$$

Under AND rule

$$Q_f = \prod_{k=1}^{K} Q(Q^{-1}((\overline{Q_d})^{\frac{1}{K}}))(1+SNR_k) + SNR_k\sqrt{\frac{N}{2}}) \ . \tag{13}$$

Similarly for the **CSUSU** scenario, the false alarm probability of the CR users' network is set constant at $\overline{Q_f}$, and the overall probability of detection can be expressed as [14]:

Under OR rule

$$Q_d = 1 - \prod_{k=1}^{K} \left(1 - Q\left(\frac{Q^{-1}(1-(1-\overline{Q_f})^{\frac{1}{K}}) - SNR_k\sqrt{\frac{N}{2}}}{(1+SNR_k)} \right) \right) . \tag{14}$$

Under AND rule

$$Q_d = \prod_{k=1}^{K} Q\left(\frac{Q^{-1}((\overline{Q_f})^{\frac{1}{K}})) - SNR_k\sqrt{\frac{N}{2}}}{(1+SNR_k)} \right) . \tag{15}$$

B. Soft Combining Rule (EGC Rule)

In soft combining rule, CR users forward the entire sensing result E_k to the fusion center without performing any local decision. The decision is made by combining these results at the fusion center by using appropriate combining rules such as Equal Gain Combining (EGC). Soft combining provides better performance than hard combining, but it requires a larger bandwidth for the control channel [11].

EGC is one of the simplest linear soft combining rules. In this method the estimated energy in each node is sent to the fusion center in which they will be added together. The summation is compared to a threshold to decide on the existence or absence of the PU. The decision statistic is given by [17]

$$E_{EGC} = \sum_{k=1}^{K} E_k \ , \tag{16}$$

where E_k denotes the statistic from the k[th] CR user. It was proved that E_{EGC} has a chi-square distribution with N*K degree of freedom. According to the central limit theorem, E_{EGC} can be approximated as a Gaussian distribution if the product NK is large enough. In this case, the overall detection probability and false alarm probability for CR users' network can be written as follows

$$Q_f = Q(\frac{\lambda - NK\sigma_w^2}{\sqrt{2NK\sigma_w^4}}) \ , \tag{17}$$

$$Q_d = Q(\frac{\lambda - NK(\sigma_w^2+\sigma_s^2)}{\sqrt{2NK(\sigma_w^2+\sigma_s^2)^2}}) \ . \tag{18}$$

From (17) and (18), we can derive the CR network probabilities under CPUP and CSUSU scenarios based on EGC combining rule.

In CPUP, we fix the probability of detection at $\overline{Q_d}$, and the Q_f is expressed as:

$$Q_f = Q(Q^{-1}(\overline{Q_d})(1+SNR) + SNR\sqrt{\frac{NK}{2}}) \ . \tag{19}$$

Similarly, Q_d under CSUSU when fixing the probability of false alarm at $\overline{Q_f}$ can be expressed as:

$$Q_d = Q(\frac{Q^{-1}(\overline{Q_f}) - SNR\sqrt{\frac{NK}{2}}}{(1+SNR)}) \ . \tag{20}$$

C. Quantized Combining Rule (Two-bit combining rule)

In [11], the authors propose a two-bit combining rule when dividing the energy region into four sub-regions and assigns different weights to each sub-region. Instead of one bit hard combining, two bits are used to indicate the decision. The presence of the signal of interest is decided at the FC when $\sum_{i=0}^{3} w_i n_i \geq L^2$, where n_i is the number of observed energies falling in region i. [11] allocates different weights for the four sub-regions, w_0=0, w_1= 1, w_2= L, and w_3= L^2. In this case, the PU is declared present if any one of the observed energies falls in region 3, or L ones fall in region 2, or L^2 ones fall in region 1, (L is a parameter to be optimized). The scheme is shown in Fig. 4, where λ_1, λ_2, and λ_3 are the thresholds for the energy detector. In [11] however, the parameter L nor λ_i are optimized.

For the two-bit combining rule with K cooperative users, the Q_f is given as [11]

$$(1-Q_f)(1+\rho)^K = \sum_{i=0}^{L^2\text{-}1}\binom{K}{i}\left\{\sum_{j=0}^{J_i}\binom{i}{j}(1-\beta_{f1})^{i-j}(\beta_{f1}-\beta_{f1}\beta_{f2})^j\right\}\rho^i \ , \tag{21}$$

with $J_i = \min\left\{\left\lfloor \frac{L^2-1-iw_1}{w_2-w_1}\right\rfloor, i\right\}$

β_{f1}= P_{f2}/P_{f1} , β_{f2}= P_{f3}/P_{f2} , and $\rho = \frac{P_{f1}}{1-P_{f1}}$. (22)

P_{fi} is the false alarm probability in region i and β_{f1}, β_{f2} are parameters to be optimized. The optimal values of β_{f1}, β_{f2} can be found numerically by maximizing the overall detection probability of the CR network Q_d given by [11]

$$Q_d = 1 - \sum_{i=0}^{L^2-1}\left(\binom{K}{i}(1-P_{d_1})^{K-1}\left\{\sum_{j=0}^{J_i}\binom{i}{j}(P_{d_1}-P_{d_2})^{i-j}(P_{d_2}-P_{d_3})^j\right\}\right) , \tag{23}$$

where P_{di} is the detection probability in region i.

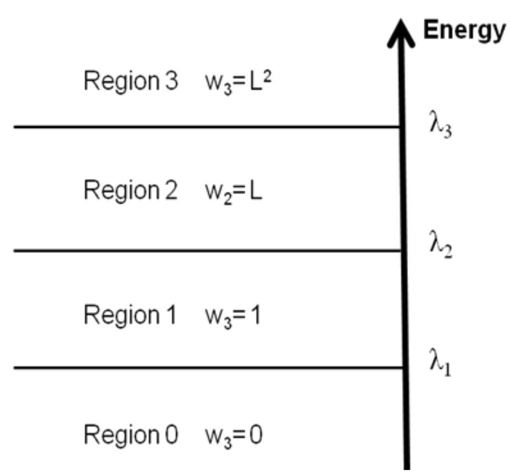

Fig. 4 The 4 energies regions for the two-bit combination

Under CPUP scenario, we fix the probability of detection at $\overline{Q_d}$, and we can rewrite (23) as

$$(1-\overline{Q_d})(1+\rho)^K =$$
$$\sum_{i=0}^{L^2-1}\binom{K}{i}\left\{\sum_{j=0}^{J_i}\binom{i}{j}(1-\beta_{d1})^{i-j}(\beta_{d2}-\beta_{d1}\beta_{d2})^j\right\}\rho^i \quad , \quad (24)$$

with $\beta_{d1}= P_{d2}/P_{d1}$, $\beta_{d2}= P_{d3}/P_{d2}$, and $\rho = \dfrac{P_{d1}}{1-P_{d1}}$. (25)

In (24), β_{d1}, β_{d2}, and L are parameters to be optimized. Similarly to [11], these parameters can be found by minimizing the overall false alarm probability given in (27) under CSUSU scenario. For our simulations, we fix the values of β_{d1}, β_{d2}, K, $\overline{Q_d}$ and L. The parameter ρ can be found numerically by solving the equation (24). Then we can find P_{d1}, P_{d2} and P_{d3} based on the values of ρ, β_{d1} and β_{d2}. Finally, the false alarm probability in each region can be computed as:

$$P_{fi} = Q(Q^{-1}(P_{di})(1+SNR) + SNR\sqrt{\frac{N}{2}}) \ . \qquad (26)$$

The overall false alarm probability of networks can be written as:

$$Q_f = 1-\sum_{i=0}^{I}\left(\begin{array}{l}\binom{K}{i}(1-P_{f_1})^{K-1}\\ \left\{\sum_{j=0}^{J_i}\binom{i}{j}(P_{f_1}-P_{f_2})^{i-j}(P_{f_2}-P_{f_3})^j\right\}\end{array}\right). \quad (27)$$

Similarly, under CSUSU and for a fixed false alarm probability $\overline{Q_f}$ and optimized values of β_{f1}, β_{f2} and L, we can use equation (22) to search ρ numerically. Then we find P_{f1}, P_{f2} and P_{f3} based on ρ, β_{f1}, β_{f2} given in (22). After that we compute the detection probability P_{di} in each region based on the following expression:

$$P_{di} = Q(\frac{Q^{-1}(P_{fi}) - SNR\sqrt{\frac{N}{2}}}{(1+SNR)}) \ . \qquad (28)$$

Finally, we can conclude the overall detection probability of networks by using the expression (23).

IV. THROUGHPUT OPTIMIZATION FOR COOPERATIVE SPECTRUM SENSING

In this section, we analyze the relationship between the CR users' capacity (throughput) and sensing capabilities for CSS under the CPUP and CSUSU scenarios.

For this study, we consider a TDM based system in which each frame consists of one sensing slot of duration (t) plus one data transmission slot of (T-t), with T is the total frame duration.

The CR users' network might operate at the PU's licensed band if the fusion center decides that the channel is idle, this occurs in two cases:

1- When the PU is inactive and the channel is declared idle, the probability of that state can be written as: $P(H_0|H_0)=P(H_0)(1-P_f)$.
2- When the PU is active and the channel is declared idle, the probability of that state can be written as: $P(H_0|H_1)=P(H_1)(1-P_d)$.

The channel utilization or the normalized capacity of the system can be expressed as [18]:

$$C = (1-\frac{t}{T})\left[(1-P_f)P(H_0) + (1-P_d)P(H_1)\right] \ . \quad (29)$$

The objective is to determine the optimal sensing time (t) such that the CR users' network throughput is maximized. In the case of CSS, this objective can be formulated as follows:

$$\max C = \left(1-\frac{t}{T}\right)\left[(1-Q_f)P(H_0) + (1-Q_d)P(H_1)\right]$$
$$\text{Subject to: } \begin{cases} 0 < \mathrm{t} < \mathrm{T} \\ Q_{\mathrm{d}} \geq \overline{Q_{\mathrm{d}}} & \text{UnderCPUP} \\ Q_{\mathrm{f}} \leq \overline{Q_{\mathrm{f}}} & \text{UnderCSUSU} \end{cases} \qquad (30)$$

Referring to [19], the optimization problem presented in (30) is a convex optimization problem if it satisfies the constraint $Q_f(t) \leq \frac{1}{2}$, which is the case for practical CR systems.

Thereafter, we can find the optimal $t^* = \mathrm{argmax}(C)$ numerically for K number of CR users and respecting the constraints given in (30) under the two scenarios CPUP and CSUSU for different combining rules presented in section III.

V. NUMERICAL EVALUATION AND RESULTS

In this section, we have performed MATLAB simulations to evaluate the optimization problem (30). It should be noted that all selected simulation parameters are based on the IEEE 802.22 WRAN. The frame duration (T) is set to 100 ms and the bandwidth channel of the PU is fixed to be 6MHz. The signal to noise ratio SNR is put to -18 dB for all K CR users.

A. *Performances detetion of CSS under CPUP and CSUSU Transmission mode*

In a first step we will evaluate the detection performances of the different schemes under the CPUP and CSUSU scenarios as a function of the sensing time.

Figure 5 shows the overall false alarm probability curves of the OR hard combining rule, the AND hard combining rule, the two-bit quantized combining rule and EGC soft combining rule over AWGN channel under CPUP scenario. For the two-bit quantized combining rule, we set L=2, β_{d1}=0.6 and β_{d2}=0.3. Under CPUP, we fix the network detection probability to 0.95 with K=10 CR users.

Figure 5 indicates that the two-bit quantized combining rule exhibits much better performance than the one-bit quantized combining rule in terms of probability of false alarm to the detriment of one bit of overhead, the EGC soft combining rule has better performance comparing to other schemes at the expense of bandwidth overhead. Therefore, the two-bit quantized combining rule achieves a good tradeoff between performance detection and overhead.

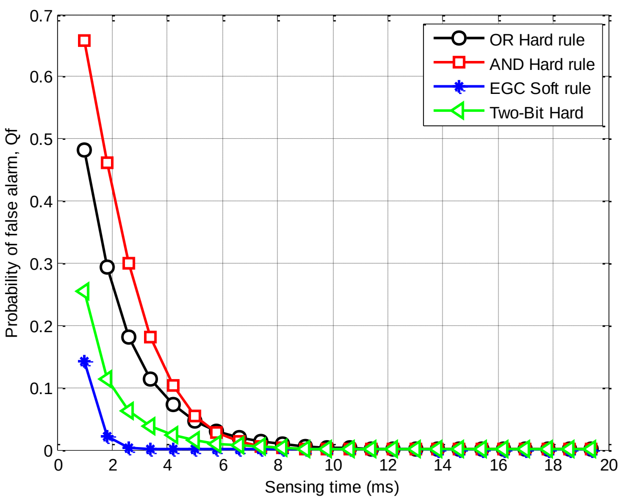

Fig. 5 Probability of false alarm versus sensing time under **CPUP** scenario using different combining rules (K=10, $\overline{Q_d}$ =0.95)

In figure 6, we plot the overall detection probability curves of the OR hard combining rule, AND hard combining rule, the quantized two-bit combining rule, and EGC soft combining rule over AWGN channel under CSUSU scenario. For the two-bit quantized combining rule, we set L=2, β_{f1}=0.25 and β_{f2}=0.1. Under CSUSU, we fix the network false alarm probability to 0.05.

As it was shown previously under CPUP, the two-bit quantized combining rule exhibits much better performance that the one-bit quantized combining rule in terms of probability of detection at the expense of one bit of overhead. The EGC soft combining rule outperforms the other rules however it requires more bandwidth overhead of reporting channel. In this case, the two-bit quantized combining rule achieves a good tradeoff between performance detection and overhead.

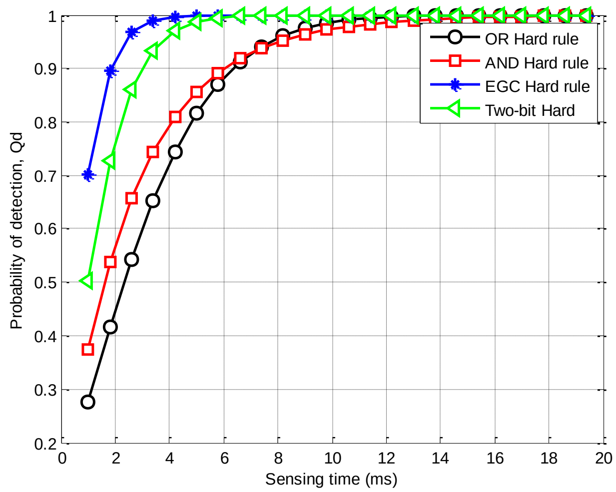

Fig. 6 Probability of detection versus sensing time under **CSUSU** scenario using different combining rules (K=10, $\overline{Q_f}$ =0.05)

B. *Capacity Optimization detetion for CSS under CPUP and CSUSU Transmission mode*

In this section, we present simulations results to show the relationship between CR users' network throughput and the sensing time for cooperative spectrum sensing. The PU absent probability on the channel is $P(H_0)$ = 0.8, and The PU present probability on the channel is $P(H_1)$ = 0.2.

Figure 7 shows the normalized capacity of the CR user's network under CPUP scenario using different combining rules. In figure 5, it was observed that that false alarm probability decreases with increasing the sensing time which suppose to increase the CR users' capacity. However, figure 7 points out that increasing the sensing time doesn't result in a monotonic increasing of the throughput of the CR users' networks. There is an optimal sensing time at which the CR users' network throughput is maximized. It is seen that the EGC soft combining rule exhibits the shortest sensing time with the highest value of capacity comparing to the other combining rules. The two-bit quantized combining rule outperforms the one-bit quantized combining rule in terms of optimal sensing time and the corresponding maximum capacity.

Figure 8 shows the normalized capacity of the CR network under CSUSU scenario using different combining rules. In figure 6, it was observed that that the detection probability increases by increasing the sensing time, this means that the PU will be more protected, however the CR users throughput will decrease as shown in figure 8. Therefore, there is no optimal sensing time as it was found under CPUP scenario, this result is trivial in the sense that the expression of the capacity is more dominated by the first term (1-Q_f) in (30) which is fixed under CSUSU scenario.

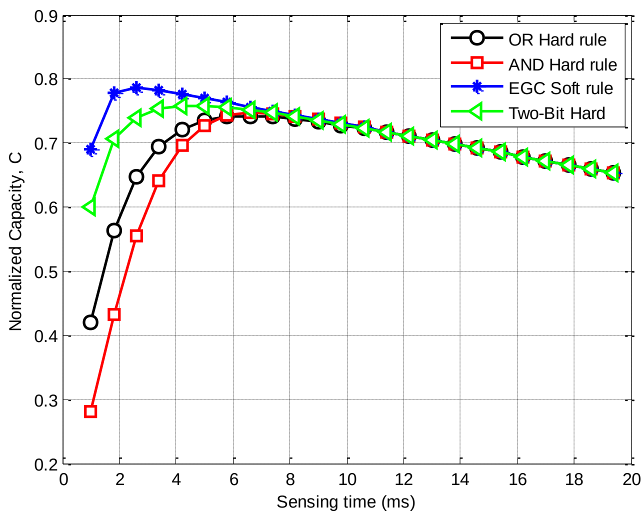

Fig. 7 Normalized capacity versus sensing time under **CPUP** scenario using different combining rules (K=10, $\overline{Q_d}$ =0.95)

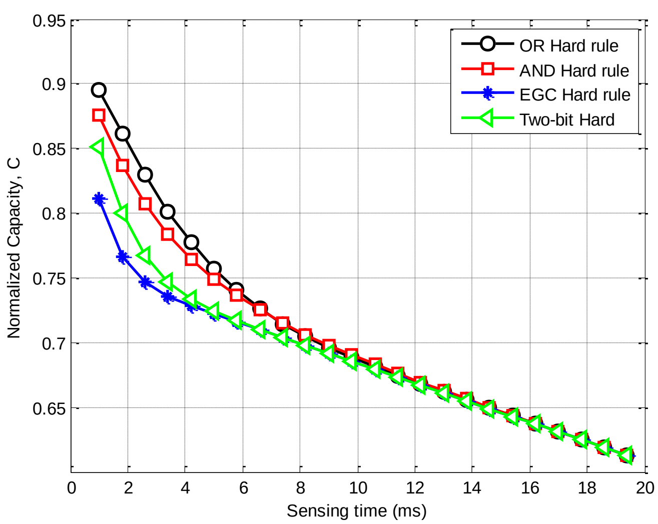

Fig. 8 Normalized capacity versus sensing time under **CSUSU** scenario using different combining rules (K=10, $\overline{Q_f}$ =0.05)

VI. CONCLUSUON

In this article, the performance of CSS has been investigated under two operational scenarios, namely, CPUP and CSUSU using different combining rules (OR, AND, EGC and the quantized two-bit). It is shown via simulations that the EGC soft combining rule outperforms the hard and the two-bit quantized combining rules and the quantized two-bit combining rule exhibits better performance detection than the hard combining rule. Further, the relationship between CR users' throughput and sensing time has been studied for both scenarios and under different combining rules. The simulation results showed that under CPUP, there is an optimal sensing time for which the CR users' network throughput is maximized. The optimal sensing time and the corresponding maximized value of the CR users' throughput depend on the combining rule used. The highest value of the throughput can be obtained by the EGC soft combining rule. The two-bit quantized combining rule which has been derived in this paper could be an appropriate combining rule to realize a tradeoff between performances (in terms of detection and throughput) and overhead (in terms of complexity and reporting channel bandwidth).

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