This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2007 proceedings.

Optimization for Cooperative Sensing in Cognitive Radio Networks

Edward Peh and Ying-Chang Liang
Institute for Infocomm Research
21 Heng Mui Keng Terrace, Singapore 119613
Email: {cypeh, ycliang}@i2r.a-star.edu.sg

***Abstract*— In cognitive radio networks, the secondary users can use the frequency bands when the primary users are not present. Hence secondary users need to constantly sense the presence of the primary users. When the primary users are detected, the secondary users have to vacate that channel. This makes the probability of detection important to the primary users as it indicates their protection level from secondary users. When the secondary users detect the presence of a primary user which is in fact not there, it is referred to as false alarm. The probability of false alarm is important to the secondary users as it will determine their usage of an unoccupied channel. Depending on whose interest is of priority, either a targeted probability of detection or false alarm shall be set. After setting one of the probabilities, the other can be optimized through cooperative sensing. In this paper, we show that cooperating all secondary users in the network does not necessary achieve the optimum performance, but instead, it is achieved by cooperating a certain number of users with the highest primary user's signal to noise ratio. Computer simulations have shown that the P_d can increase from 92.03% to 99.88% and P_f can decrease from 6.02% to 0.06% in a network with 200 users.**

I. INTRODUCTION

A recent study by Federal Communications Commission (FCC) shows that most of the allocated spectrum in US is under-utilized [1]. A promising technology, called cognitive radio [2],[3],[4], can be used to enable frequency reuse of these under-utilized spectrum. In fact, in December 2003, FCC identifies cognitive radio as the candidate for implementing negotiated/opportunistic spectrum sharing [8]. In response to this, the IEEE has formed the 802.22 Working Group to develop a standard for wireless regional area networks (WRAN), reusing the TV bandwidth based on cognitive radio technology [9].

In frequency reuse based cognitive radio, the unlicensed (secondary) users are able to use the frequency bands when they sense that no licensed (primary) users are using those bands. Hence channel sensing is an important aspect of cognitive radio. In channel sensing, two probabilities are of interest. First, the probability of detecting the primary users when the primary users are active. This probability indicates how well the primary users are protected since the secondary users have to vacate the channel once the primary users are detected. The other probability is the probability of detecting the primary users when the primary users are not active, which is referred to as probability of false alarm. If the false alarm probability is high, the usability of an unoccupied channel by the secondary users are low since the secondary users will still have to vacate the channel when there is no primary users. This will decrease the achievable throughput of the secondary users.

To give the primary users their desired level of protection, the probability of detection can be set at a fixed value while the probability of false alarm is reduced as much as possible through cooperative sensing. Cooperative sensing is the process of making a final decision for the network based on the sensing data collected from various distributed secondary users. Cooperative sensing can improve the probabilities of detection and false alarm [6],[7]. In this paper, given a targeted probability of detection for the network, we find the achievable minimum probability of false alarm in the network. From the other perspective, the usage level for unoccupied channels can be fixed by setting the probability of false alarm at a fixed value while the probability of detection is maximized as much as possible through cooperative sensing. In this paper, we also find the achievable maximum probability of detection in the network, with the given targeted probability of false alarm. We prove that the two optimum probabilities mentioned above are achieved by cooperating a certain number of users with the highest primary user's signal to noise ratio rather than cooperating all the users within the network. Cooperative sensing using AND and OR fusion schemes with energy detector are used to present our results.

This paper is organized as follows. In Section II, we define the system model of the cognitive radio network that is used in our analysis and simulations. Section III gives the review of channel sensing hypothesis, energy detector and cooperative sensing. Section IV provides the analysis of optimization for cooperative sensing. Performance evaluations and comparisons are given in Section V. The conclusions are drawn in Section VI.

II. SYSTEM MODEL

The system setup used in this paper is based on the IEEE 802.22 WRAN deployment scenario. This system model is illustrated in Fig. 1, which includes a TV broadcast station as the primary user, a WRAN base station (BS) as the secondary base station and customer-premises equipments (CPEs) as the secondary users. The primary user and the secondary BS are far apart and the secondary users are randomly distributed within the coverage radius of the secondary BS. The distances between each secondary users and primary user are assumed to be known at the BS and this assumption comes from IEEE 802.22 which requires the WRAN base station to know the distances of all the CPEs to the TV station. With the distances

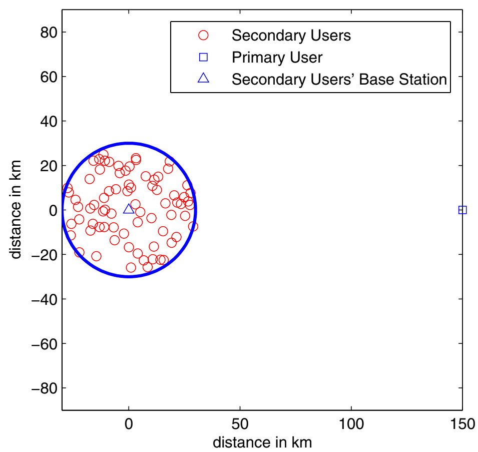

Fig. 1. Topology of Cognitive Radio Network.

known, the received power of user i is,

$$P_i = \frac{P_{pu}}{d_i^{\alpha}}\beta, \tag{1}$$

where P_{pu} is the primary user's signal power, d_i is the distance between ith secondary user and primary user, α is the path loss exponent factor and β is a scalar. The primary user's signal to the noise ratio received at each secondary user is computed by

$$\gamma_i = 10 \log \frac{P_i}{\sigma^2}, \quad \text{for} \quad i = 1, ..., M \tag{2}$$

where σ^2 is the noise power and M is the total number of secondary users in the system. The analysis and simulations in Section IV and in Section V will be based on this system model. In reality, if the distances are unknown to the secondary BS, the secondary users can transmit their γ_i to the secondary BS.

III. Channel Sensing

A. Channel Sensing Hypothesis

In a cognitive radio system, when the secondary users are sensing the channel, the sampled received signal of the secondary users have two hypothesis. Hypothesis $\mathcal{H}_1$, is the primary user is active and hypothesis $\mathcal{H}_0$, is the primary user is inactive.

$$\mathcal{H}_1: \quad y(n) = s(n) + u(n), \tag{3}$$

$$\mathcal{H}_0: \quad y(n) = u(n), \tag{4}$$

where $s(n)$ is the primary user's signal and is assumed to be an iid random process with mean zero and variance, σ_s^2. The noise, $u(n)$, is assumed to be Gaussian iid random process with zero mean and variance, σ_u^2. $s(n)$ and $u(n)$ are assumed to be independent.

In channel sensing, we are interested in the probability of detection, P_d, and the probability of false alarm, P_f. P_d and P_f are defined as the probabilities that a sensing algorithm detects a primary user under hypothesis $\mathcal{H}_1$ and $\mathcal{H}_0$, respectively. Whenever a primary user is detected, the secondary network has to vacate that channel. Hence, the higher the P_d, the higher is the protection level given to the primary users from the secondary users. While the lower the P_f, the higher is the reusability of the unoccupied channel. A good sensing algorithm should therefore have a high P_d and a low P_f.

B. Energy Detector

We use energy detector as the channel sensing scheme to present our results. The test statistic for energy detector is given by

$$T(y) = \frac{1}{N}\sum_{n=1}^{N} |y(n)|^2. \tag{5}$$

Under $\mathcal{H}_0$, the test static $T(y)$ is a random variable whose probability density function (PDF) is a chi-square distribution with $2N$ degrees of freedom. Using central limit theorem, for a large N, the PDF of $T(y)$ can be approximated by a Gaussian distribution with

$$\begin{array}{ll} \text{mean:} & \mu_0 = \sigma_u^2 \\ \text{variance:} & \sigma_0^2 = \frac{1}{N}[\mathsf{E}|u(n)|^4 - \sigma_u^4]. \end{array}$$

If $u(n)$ is circular symmetric complex Gaussian (CSCG), then $\mathsf{E}|u(n)|^4 = 2\sigma_u^4$, and thus, $\sigma_0^2 = \frac{1}{N}\sigma_u^4$. For a chosen threshold ϵ, the probability of false alarm is given by

$$\begin{aligned} P_f(\epsilon) &= Pr(T(y) > \epsilon|\mathcal{H}_0) \\ &= \frac{1}{\sqrt{2\pi}\sigma_0}\int_{\epsilon}^{\infty} e^{-(T(y)-\mu_0)^2/2\sigma_0^2} \\ &= \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - 1\right)\sqrt{N}\right), \end{aligned} \tag{6}$$

where $\mathcal{Q}(\cdot)$ is the area under the tail of a Gaussian PDF.

Using central limit theorem, the PDF of $T(y)$ under $\mathcal{H}_1$, can also be approximated by a Gaussian distribution with

$$\begin{array}{ll} \text{mean:} & \mu_1 = (\sigma_s^2 + \sigma_u^2) \\ \text{variance:} & \sigma_1^2 = \frac{1}{N}[\mathsf{E}|s(n)|^4 + \mathsf{E}|u(n)|^4 - (\sigma_s^2 - \sigma_u^2)^2], \end{array}$$

where $s(n)$ and $u(n)$ are both circular symmetric and complex. Assume $s(n)$ is a complex PSK modulated signal and $\mathsf{E}|s(n)|^4 = \sigma_s^4$, then $\sigma_1^2 = \frac{1}{N}(2\gamma + 1)\sigma_u^4$. We defined $\gamma = \frac{\sigma_s^2}{\sigma_u^2}$ as the primary user's signal power to noise ratio received at the secondary user. For a chosen threshold ϵ, the probability of detection is given by

$$\begin{aligned} P_d(\epsilon) &= Pr(T(y) > \epsilon|\mathcal{H}_1) \\ &= \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - \gamma - 1\right)\sqrt{\frac{N}{2\gamma + 1}}\right). \end{aligned} \tag{7}$$

For a targeted detection probability, $\bar{P}_d$, the probability of the false alarm using the energy detector is given by substituting (7) into (6),

$$P_f = \mathcal{Q}\left(\sqrt{2\gamma + 1}\mathcal{Q}^{-1}(\bar{P}_d) + \sqrt{N}\gamma\right). \tag{8}$$

While, for a targeted false alarm probability, $\bar{P}_f$, the probability of the detection using the energy detector is given by substituting (6) into (7),

$$P_d = \mathcal{Q}\left(\frac{1}{\sqrt{2\gamma+1}}\left(\mathcal{Q}^{-1}(\bar{P}_f) - \sqrt{N}\gamma\right)\right). \quad (9)$$

C. Cooperative sensing

There are many challenges in channel sensing [5], and one of the ways to improve channel sensing reliability is through cooperative sensing. Cooperative sensing is done by fusion the sensing data of individual secondary users and make a final decision at the secondary BS. To minimize the transmission overhead of the sensing data, every secondary users will make their own sensing decision and transmit their one-bit decision to the secondary BS for fusion. The optimum decision fusion rule is Chair-Varshney rule [10], which is based on log likelihood ratio test. In this paper, we will use AND and OR fusion rules because given a targeted probability of detection $\bar{P}_d$, or a targeted probability of false alarm $\bar{P}_f$, the individual secondary users' threshold can be easily derived and the sensing performance can be evaluated.

In OR fusion rule, when at least 1 out of k secondary users detect the primary users, the final decision declares a primary user is present. The P_d and P_f of the final decision are therefore, respectively

$$P_d = 1 - \prod_{i=1}^{k}(1 - P_{d,i}), \quad (10)$$

$$P_f = 1 - \prod_{i=1}^{k}(1 - P_{f,i}), \quad (11)$$

where $P_{d,i}$ and $P_{f,i}$ are respectively, the probability of detection and false alarm of the ith secondary user. k is the number of users cooperating. In AND fusion rule, the final decision declares a primary user is present only when all the k secondary users detect the primary users. The P_d and P_f of the final decision are, respectively,

$$P_d = \prod_{i=1}^{k} P_{d,i}, \quad (12)$$

$$P_f = \prod_{i=1}^{k} P_{f,i}. \quad (13)$$

IV. Optimizing Cooperative Sensing Performance

In this paper, we look at the optimization problem from two perspectives. From the primary users' perspective, a guaranteed high P_d to protect them is what they desired. In this case, we fix the P_d of the network at their desired value and then minimize P_f as much as possible. From the secondary users' perspective, a guaranteed low P_f is desired so that they will have a high capacity. This perspective turns out to be a Neyman-Pearson detection problem [11], where the P_f of the network is fixed at a desired value and P_d is maximized as much as possible. In reality, there is always a minimum targeted P_d set to protect the primary users. Hence when fixing P_f and maximizing P_d, the maximized P_d should be always at least higher than the minimum targeted P_d. Any increase in P_d above the minimum targeted P_d when maximizing is an additional protection to the primary user.

A. Constant Detection Rate

1) OR rule: As mentioned above, from the primary users' perspective, the probability of detection is fixed at a targeted value, $\bar{P}_d$. We define this as constant detection rate (CDR) requirement. When using OR fusion rule in CDR, from (10) the individual secondary users' targeted probability of detection is given by

$$\bar{P}_{d,i} = 1 - \sqrt[k]{1 - \bar{P}_d} \quad for \quad i = 1, ..., k, \quad (14)$$

where k is the number of users used for cooperation out of the M total number of users in the network. With the computed $\bar{P}_{d,i}$ and by substituting (14) into (8), the probability of false alarm of each secondary user is given as,

$$P_{f,i} = \mathcal{Q}\left(\sqrt{2\gamma_i + 1}\,\mathcal{Q}^{-1}(1 - \sqrt[k]{1 - \bar{P}_d}) + \sqrt{N}\gamma_i\right) \quad for \quad i = 1, ..., k, \quad (15)$$

where γ_i is the primary user's signal to noise ratio received at the ith secondary user. The total P_f of the network is derived by substituting (15) into (11). We analyze (15) and (11) to find the optimum (minimum) P_f of the network. From (15), the higher the γ_i, the lower the $P_{f,i}$, hence secondary users with the highest γ_i values should be chosen first for cooperation. So users included for the cooperation should always start from the users with highest γ_i. When an additional user is included into the cooperation (k increases), it helps to decrease $P_{f,i}$ of others in the cooperation with its own $P_{f,i}$ the highest since it has the lowest γ_i among the k users. Fig. 2(a) shows the maximum $P_{f,i}$, which is $P_{f,k}$, as k increases from 1 to 100 in a network consisting of 100 users. $P_{f,k}$ decreases sharply initially because of the $\mathcal{Q}^{-1}\left(1 - \sqrt[k]{1 - \bar{P}_d}\right)$ term in (15) but because γ_k is decreasing as k increases, the $P_{f,k}$ rises back. The P_f of the network will therefore decrease because of the rapid decrease of individual $P_{f,i}$ in the lower k region but P_f of the network will eventually rise back because of two factors; first, from Fig. 2(a), the $P_{f,k}$ is increasing at the higher k region and secondly the OR fusion scheme (11), is an increasing function as k increases. This shows that the number of users to achieve optimum P_f of the network must lies at $1 < k < M$. Using all the secondary users for cooperation does not obtain the lowest P_f. The number of cooperating users to obtain the optimum P_f is computable from (14), (15) and (11) at the secondary base station when every secondary users' γ_i are known to the secondary base station.

2) AND rule: We now analyze the performance of AND fusion rule under CDR. For a given targeted probability of detection $\bar{P}_d$ for the network, from (12) the individual secondary users' targeted probability of detection is given by

$$\bar{P}_{d,i} = \sqrt[k]{\bar{P}_d} \quad for \quad i = 1, ..., k. \quad (16)$$

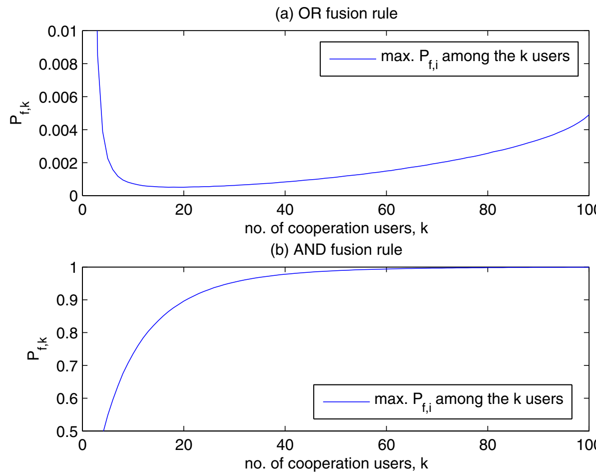

Fig. 2. The maximum $P_{f,i}$ in the network under CDF requirement.

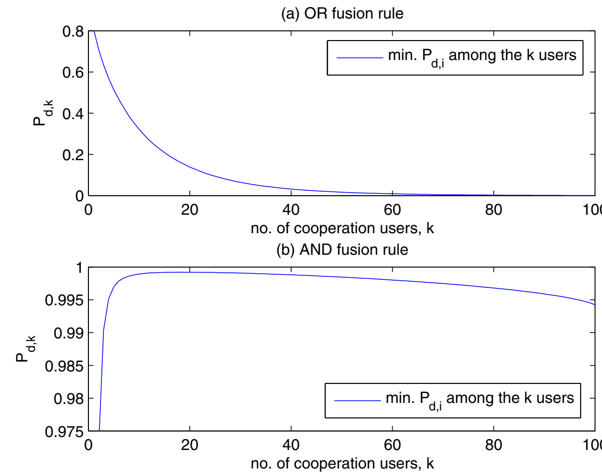

Fig. 3. The minimum $P_{d,i}$ in the network under CFAR requirement.

By substituting (16) into (8), the probability of false alarm of each secondary user is given by,

$$P_{f,i} = \mathcal{Q}\left(\sqrt{2\gamma_i+1}\mathcal{Q}^{-1}(\sqrt[k]{\bar{P}_d}) + \sqrt{N}\gamma_i\right) \quad for \quad i = 1, ..., k. \tag{17}$$

Because of the term $\mathcal{Q}^{-1}(\sqrt[k]{\bar{P}_d})$ in (17), $P_{f,i}$ increases as k increases. So when an additional user is added into the cooperation, that user will increase all other users' $P_{f,i}$ in the cooperation with its own $P_{f,i}$ being the highest. The maximum (worst) $P_{f,i}$, which is $P_{f,k}$, is plotted on Fig. 2(b) and it is shown to be exponentially increasing as k increases. However, the AND fusion scheme, (13), is an exponentially decreasing function as k increases. As (17) is exponentially increasing and (13) is exponentially decreasing, it is difficult to show that the optimum (achievable minimum) P_f is at $1 < k < M$ but given all the secondary users' γ_i, the k to achieve optimum P_f, can be computed out at the secondary base station with (16), (17) and (13). We will show that cooperating all M users does not obtain the optimum P_f by simulation.

B. Constant False Alarm Rate

1) OR rule: If a guaranteed usability rate of an unoccupied channel is needed, the P_f of the network has to be fixed and the P_d of the network is maximized as much as possible. This is referred to as constant false alarm rate (CFAR) requirement. In the OR fusion rule, to achieve a targeted probability of false alarm $\bar{P}_f$ for the network, from (11) the individual secondary users' targeted probability of false alarm, $\bar{P}_{f,i}$, is given by,

$$\bar{P}_{f,i} = 1 - \sqrt[k]{1-\bar{P}_f} \quad for \quad i = 1, ..., k. \tag{18}$$

With the $\bar{P}_{f,i}$, the probability of detection of each cooperating secondary users, $P_{d,i}$, is given as, by substituting (18) into (9),

$$P_{d,i} = \mathcal{Q}\left(\frac{1}{\sqrt{2\gamma_i+1}}\left(\mathcal{Q}^{-1}\left(1-\sqrt[k]{1-\bar{P}_f}\right) - \sqrt{N}\gamma_i\right)\right) \quad for \quad i = 1, ..., k. \tag{19}$$

From (19), the larger the γ_i, the larger is the $P_{d,i}$. Hence, same as CDR, secondary users with the highest γ_i should always be chosen first for the cooperation. When an additional user is included into the cooperation, not only itself has the lowest $P_{d,i}$ but it also decreases the $P_{d,i}$ of the rest because of the term $\mathcal{Q}^{-1}\left(1-\sqrt[k]{1-\bar{P}_f}\right)$ in (19), which decreases $P_{d,i}$ as k increases. The minimum (worst) $P_{d,i}$, which is $P_{d,k}$, is plotted in Fig. 3(a) and is shown to be exponentially decreasing as k increases. Although (19) is exponentially decreasing, the OR fusion rule (10), is an exponentially increasing function as k increases. Given the γ_i values of the secondary users, the optimum P_d of the network can be computed out and the number of cooperating users, k, that obtain the optimum P_d can be found.

2) AND rule: Using AND fusion rule for CFAR, the targeted probability of false alarm for the network, $\bar{P}_f$, is achieved by targeting the individual secondary users' probability of false alarm $\bar{P}_{f,i}$, at

$$\bar{P}_{f,i} = \sqrt[k]{\bar{P}_f} \quad for \quad i = 1, ..., k. \tag{20}$$

With the $\bar{P}_{f,i}$, the probability of detection of each cooperating secondary users, $P_{d,i}$, is given by substituting (20) into (9),

$$P_{d,i} = \mathcal{Q}\left(\frac{1}{\sqrt{2\gamma_i+1}}\left(\mathcal{Q}^{-1}\left(\sqrt[k]{\bar{P}_f}\right) - \sqrt{N}\gamma_i\right)\right) \quad for \quad i = 1, ..., k. \tag{21}$$

From (21), because of the term $\mathcal{Q}^{-1}\left(\sqrt[k]{\bar{P}_f}\right)$, when an additional user is included into the cooperation, it helps to increase the other users' $P_{d,i}$ in the network but its own $P_{d,i}$ will be the lowest as it has the lowest γ_i. Hence we plot out the minimum (worst) $P_{d,i}$, which is $P_{d,k}$, as k increases in Fig. 3(b). As shown in the figure, the $P_{d,k}$ is increasing rapidly because of the $\mathcal{Q}^{-1}\left(\sqrt[k]{\bar{P}_f}\right)$ term but as k keeps on increasing, the $P_{d,k}$ reduces because the γ_k becomes smaller. From this, we conclude that P_d of the network will increase initially as all the $P_{d,i}$ are increasing exponentially, however, the AND fusion rule (12), which is a decreasing function, and the decreasing γ_k will eventually bring the P_d down. Hence, the optimum P_d lies at $1 < k < M$ and using all the M users for cooperation will definitely not obtain the optimum P_d.

V. Computer Simulation Results

Computer simulation results are presented to evaluate the optimum P_f of the network under CDR requirement and the optimum P_d of the network under CFAR requirement. The parameters used in our simulations of the cognitive radio network shown in Fig. 1 are as follows. The secondary users are randomly distributed within the 30km radius of the secondary users' BS. The secondary BS is 150km away from the primary user. During the sensing time, the number of received signal samples at each secondary users is set as 6000 samples. The path loss exponent factor α, in (2), is set to be 3.5. The β and P_{pu} are set at a value such that the primary user's signal to noise ratio at the secondary BS is -16dB. Either d_i or the γ_i is assumed to be known to the secondary BS.

A. CDR

Under the CDR requirement, the targeted probability of detection $\bar{P}_d$ is set at 99.9%. The total number of secondary users M, in the network, is set to be 50, 100, 150 and 200. Fig. 4 shows the P_f of the network as the number of cooperating users increases. For both the OR and AND fusion schemes, the P_f decreases initially and rises back eventually as k increases to M. The simulation results tally with the analysis in Section IV, and it shows that cooperating a certain number of secondary users with the highest γ_i has a better performance than cooperating all the secondary users available in the network. Fig. 5 shows the optimum P_f of the network and the P_f of the network when all of the secondary users are cooperated. They are plotted against the total number of users in the network. The (k, M) in the figure represents the number of cooperating users k needed out of the total users in the network M to achieve the optimum P_f. For OR fusion scheme, when using all the secondary users for cooperation, the P_f is always much higher than the optimum P_f. For a network consisting 200 secondary users, the P_f when cooperating all users, is 6.02% compared to the optimum P_f, 0.06%, for which only 19 users are cooperated. For the AND fusion scheme, when the number of secondary users in the network is small, P_f of cooperating all users is much higher than the optimum P_f. When the number of secondary users is large, the difference in performance is narrowed. For AND fusion scheme, the optimum P_f in a network of 200 users occurs when 36 users with the highest γ_i are cooperated, and the value is 0.03%. To refresh your memory, the number of cooperating users needed to achieve the optimum P_f is computable at the secondary BS when the BS knows all the secondary users' γ_i.

B. CFAR

Under the CFAR requirement, the targeted probability of false alarm of the network $\bar{P}_f$, is set at 0.1%. Fig. 6 shows the P_d of the network, when the number of cooperating users in the network increases. For both OR and AND fusion schemes, the P_d increases initially and decreases back as k increases. This tally with the analysis in Section IV, that cooperating a certain number of users with the highest γ_i provides the highest P_d instead of using all the secondary users for cooperation. Fig. 7 compares the optimum P_d with the P_d when all the secondary users are used for cooperation. When AND fusion scheme is used in a network consisting 200 secondary users, P_d of cooperating all users is 92.04% compared to the optimum P_d, 99.88%, for which 19 users are cooperated. For OR fusion scheme, the difference is less visible when the number of secondary users in the network is large. The optimum P_d in a network of 200 users is when 46 users are cooperated and the value is 99.99%.

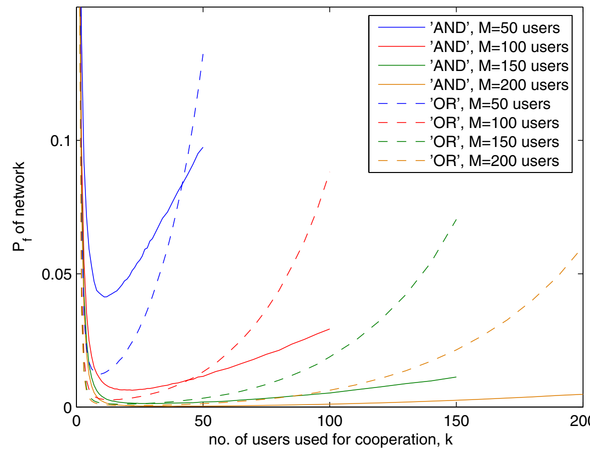

Fig. 4. The P_f of the network as the no. of cooperation users increase in AND and OR fusion scheme under CDR requirement.

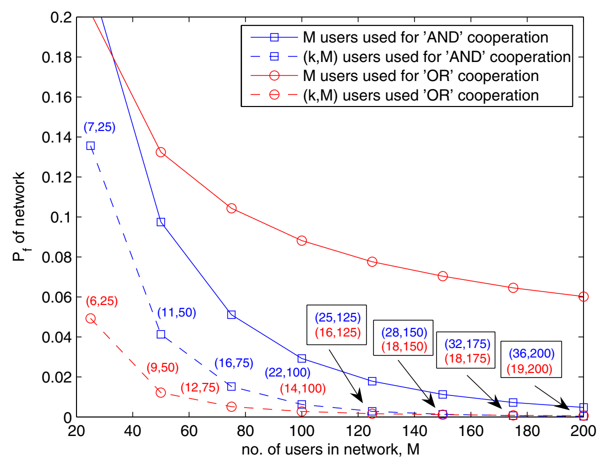

Fig. 5. Under CDR requirement, comparison of optimum P_f of the network with P_f when all users are collaborated.

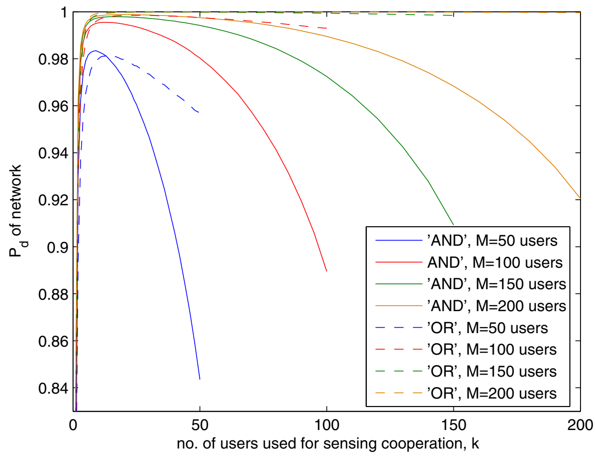

Fig. 6. The P_d of the network as the no. of cooperation users increase in AND and OR fusion scheme under CFAR requirement.

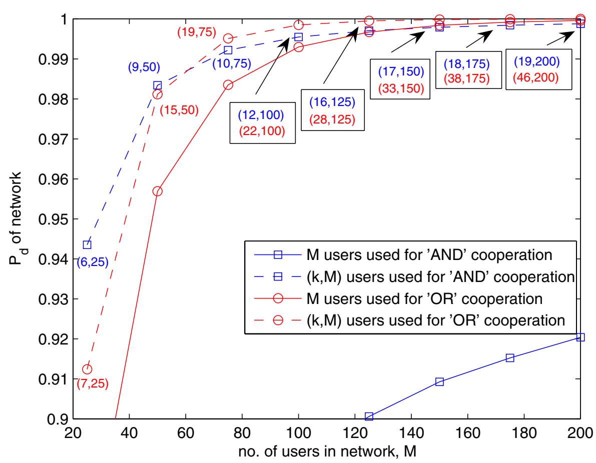

Fig. 7. Under CFAR requirement, comparison of optimum P_d of the network with P_d when all users are collaborated.

VI. Conclusions

In this paper, we showed that cooperating all secondary users in the network does not achieve the optimum P_f or P_d. The optimum P_f or P_d is usually achieved by cooperating a group of users that have higher primary user's signal to noise ratio, γ_i. The number of cooperating users to obtain the optimum P_f or P_d is computable at the secondary BS if the BS knows every users' γ_i. To achieve the best performance, we should do a computation first at the BS and cooperate those users that can obtain the optimum performance rather than cooperating all users. Computer simulations have shown that in CDR with OR fusion scheme, when cooperating 19 secondary users instead of all 200 secondary users in the network, the P_f decreases from 6.02% to 0.06%. In CFAR with AND fusion scheme, when cooperating 19 secondary users instead of all 200 users in the network, the P_d is increased from 92.04% to 99.88%.

References

[1] Federal Communications Commission, "Spectrum policy task force report, FCC 02-155." Nov. 2002.

[2] J. Mitola and G. Q. Maguire, "Cognitive radios: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 1318, Aug. 1999.

[3] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Doctor of Technology, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

[4] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, Feb. 2005.

[5] A. Sahai and D. Cabric, "Spectrum sensing: fundamental limits and practical challenges," *Proc. IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore, MD, Nov. 2005.

[6] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio networks," *Dyspan'2005*, pp. 137-143, Nov. 2005.

[7] S. M. Mishra, A. Sahai, and R. W. Broderson, "Cooperative sensing among cognitive radios," *Proc. IEEE International Conference on Comunications (ICC) 2006*, Istanbul, Turkey, Jun. 2006.

[8] Federal Communications Commission,, "Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies, notice of proposed rule making and order, FCC 03-322." Dec. 2003.

[9] IEEE 802.22 Wireless RAN, "Functional requirements for the 802.22 WRAN standard, IEEE 802.22 - 05/0007r46," Oct. 2005.

[10] Z. Chair and P.K. Varshney, "Optimal data fusion in multiple sensor detection systems," *IEEE Trans. on Aerospace and Elect. Syst.*, vol.22 pp.98-101, January 1986.

[11] P. K. Varshney, "*Distributed Detection and Data Fusion*". Springer, 1997.