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Distributed Cooperative Spectrum Sensing in Cognitive Radio Networks with Adaptive Detection Threshold

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Abstract: This paper proposes a cooperative sensing algorithm based on distributed fusion strategy and maintained probability of false alarm for cognitive radio. It further introduces a reporting strategy that discusses how cooperative sensing in distributed manner can select among possible candidates in order to reduce bandwidth requirement. We adopted a dynamic distributed architecture for cooperative sensing based on the link quality and found condition on the channel quality for cooperation to be beneficial. Using probability of detection, and BER metrics we evaluated the performance improvement of distributed cooperation over direct cooperation and non-cooperative sensing. We used analytical formulation with possible candidate selection criteria to investigate and maximize the cooperation gain. By employing such distribution and selection technique, the reporting error due to the fading channel is reduced. Results show that the method effectively improve performance of sensing, it increase the probability of detection up to 0.9 at <0.1 probability of false alarm. Sensitivity requirement is reduced with network scale and the number of nodes participate in decision fusion is reduced about 42% at probability of false alarm 0.1. ROC curve has obvious improvement compared with existing methods.

Keywords: cognitive radio; cooperative sensing; distribution; adaptive detection.

1. Introduction

Cognitive radio has the potential for making a significant difference to the way in which the radio spectrum can be accessed with improved utilization of the spectrum as a primary objective

[1]. However, the realization of cognitive radio requires strong grantee of no interference to primary user. This motivates research in spectrum sensing and its related technologies. Local sensing is not fitting the requirements for reliable detection of primary users due to its limitation in fading environment [2]. Therefore, cooperative sensing is introduced as the key to reducing the probability of interference to legacy systems [3]. However, cooperative gains are based on validity/reliability of sensing, control channel, and the network's cooperation protocol. Uncertainty regarding noise and interference imposes fundamental limits on how sensitive cooperative sensing can be. Moreover, cooperative sensing requires a combination of a large cooperative technologies including data fusion algorithms, data exchange protocol, and network architecture. Table I summarize main characteristic of existing cooperative method and identify their drawbacks. Based on this we motivate the strong need for advanced sensing methods and established sensing to be a distributed cooperative method.

Table1. Existing Cooperative Methods

Sensing method	**Network Architecture**	**Considered Problem**	**Shortage/drawback**
Energy detection	Centralized [5]	fading impact in sensing channel and hidden node problem	– Complexity in decision fusion – Impact of Reporting channel – Based on basic energy detection – Probability of detection bounded with probability of false alarm – Channel BW
	Adhoc [5]		
	Cluster-Based [4]	Complexity in decision fusion and Impact of Reporting channel	– Based on basic energy detection – Probability of detection bounded with probability of false alarm
	Cluster-Based [6]	Design of link layer protocol and effect of node mobility	– Effects of transmission errors and nodes connectivity on quality of detection – Protocol time and synchronization issues
Feature detection	Distributed [7]	feature detection	Detection of unknown signal
Relay based	Two user [8]	Primary user detection	Risk of interfering with primary user in transmitting slot
	Multi-user [9]		

2. System Model

In our model, cognitive radio CRs operate in distributed cooperative manner; that divide CRs population into groups, each of which select the node with the best reporting channel gain as a fusion node. The CRs conduct local sensing based on maintained energy detection and forward their binary detection decision to fusion node where the processing and fusion of local spectrum observation for candidate nodes is made, the modeling flow is shown in Fig. 1. The flow chart as shown in Fig. 2 illustrate the formation of DCS network architecture and the selection of fusion nodes based on the reporting channel SNR to fusion centre. It also show the possible actions for node leaving and joining the network, however we consider no change in architecture during sensing period and no node mobility. The DCS is modeled with a standard parallel fusion network. A schematic representation of distributed cooperation is illustrated in Fig. 3; each fusion node calculates its group decision. It then sends the result to the fusion centre through a best control channel. The fusion centre computes the global decision, from the outputs of the fusion nodes.

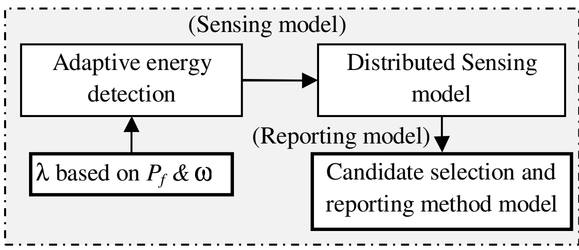


Figure 1. Modeling diagram

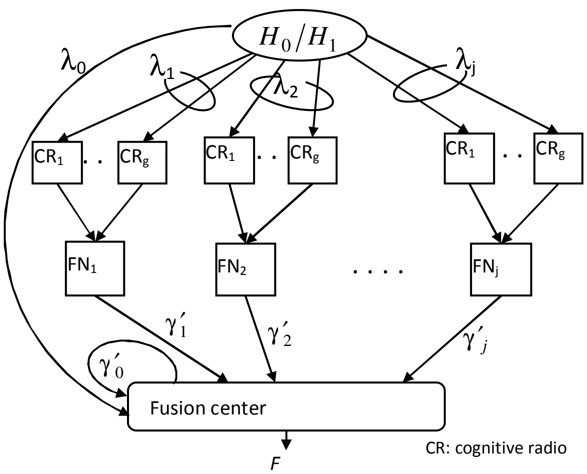


Figure 3. Schematic representation of distributed cooperation for spectrum sensing

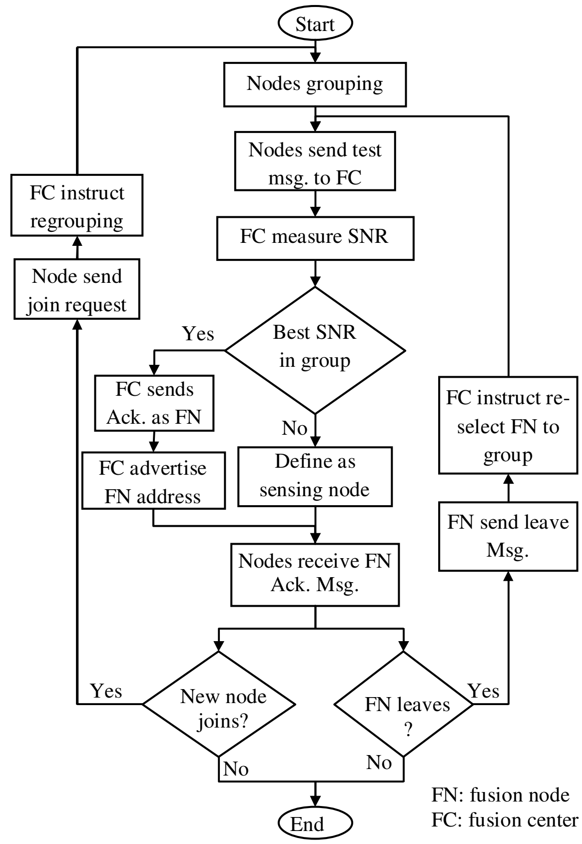


Figure 2. Network formation and fusion nodes selection

2.1 Detection model

The basic problem concerning spectrum sensing is the detection of a signal within a noisy measure. We assume that prior knowledge of the primary user signal is not known. Therefore, optimal detector based on matched filter is not an option since it would require the knowledge of the data for coherent processing. Instead a suboptimal energy detector is adopted, which can be applied to any signal type. We assume the noise is additive white Gaussian with zero mean and power spectral density. We consider a low-mobility environment, so we assume that during the course of the transmission, or for each sensing period, each user observes only one fading level towards the fusion node/fusion centre. Due to the spatial separation between users, the channels corresponding to different cognitive users are assumed to be independent. All channels are assumed to experience Rayleigh fading. Therefore, the received signal at the secondary receiver has the following simple form,

$$s[n] = hx[n] + w[n] \quad (1)$$

where $x[n]$ is the signal to be detected, $w[n]$ is the additive white Gaussian noise (AWGN), h is the channel fading coefficient, and n is the sample index. Note that $x[n] = 0$ when there is no transmission by a primary user. The received signal at cognitive radio has one of the following hypotheses, Busy channel, H_1, which indicate primary user present and White space/Spectrum hole/Idle channel, H_0, that indicate primary user absent

$$\begin{aligned} H_1 &: \quad s[n] = hx[n] + w[n] \\ H_0 &: \quad s[n] = w[n] \end{aligned} \quad (2)$$

The energy detection based sensing metric can be obtained as [10],

$$M = \sum_{n=0}^{N-1} s[n] \quad (3)$$

2.2 DCS model

Using the same model given on equation (1), if the number of sample is large enough, chi-squared distribution is approximated to Gaussian distribution based on the central limit theorem, the test statistics M are asymptotically normally distributed with mean

$$\mu = \begin{cases} 2n\sigma_s^2 & H_0 \\ (2n + \gamma)\sigma_s^2 & H_1 \end{cases} \quad (4)$$

and variance.

$$\sigma^2 = \begin{cases} 4n\sigma_s^2 & H_0 \\ 4(n + \gamma)\sigma_s^2 & H_1 \end{cases} \quad (5)$$

then the metric M under the hypothesis H_1, H_0 is expressed by,

$$M|H_1 \sim \mathcal{N}(\mu_{x+w}, \sigma_{x+w}) \quad (6)$$

$$M|H_0 \sim \mathcal{N}(\mu_{\omega}, \sigma_{\omega}) \quad (7)$$

where $\mathcal{N}(\alpha, \beta)$ denote Gaussian distribution with mean α and variance β, and for N sample $\mu_{x+w} = N\mathrm{E}(x^2[n]) + N\mathrm{E}(w^2[n]) = N\sigma_x^2 + N\sigma_w^2$, $\sigma_{x+w} = 4N\mathrm{E}(x^2[n]) + 2N\mathrm{E}(w^2[n]) = 4N\sigma_x^2 + 2N\sigma_w^2$, $\mu_{\omega} = N\mathrm{E}(w^2[n]) = N\sigma_w^2$, and $\sigma_{\omega} = 2N\sigma_w^2$.

Let $\mu_0 = \mu, H_0$, $\sigma_0 = \sigma, H_0 \mu_1 = \mu, H_1$ and $\mu_1 = \mu, H_1$, $\sigma_1 = \sigma, H_1$ then, CR users will have the following probabilities of detection and false alarm:

$$P_d = Q\left(\frac{\lambda - \mu_0}{\sigma_0}\right) = \int_{\frac{\lambda-\mu_0}{\sigma_0}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{\lambda-\mu_0}{2\sigma_0}} d\lambda \quad (8)$$

$$P_f = Q\left(\frac{\lambda - \mu_1}{\sigma_1}\right) = \int_{\frac{\lambda-\mu_1}{\sigma_1}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{\lambda-\mu_1}{2\sigma_1}} d\lambda \quad (9)$$

To maintain the receiver operating characteristic (ROC) the detection threshold λ is determined by a given P_f as:

$$\lambda = \mu_{\omega} + \sqrt{\sigma_{\omega}} Q^{-1}\left(P_f\right) \tag{10}$$

P_d and P_f for the local node sensing can be calculated as:

$$P_d = Q\left(\lambda - N\left(\sigma_x^2 + \sigma_w^2\right) \Big/ \sqrt{2N\left(2\sigma_x^2 + \sigma_w^2\right)^2}\right) \tag{11}$$

$$P_f = Q\left(\lambda - N\sigma_w^2 \Big/ \sqrt{2N\sigma_w^2}\right) \tag{12}$$

Assume each sensing group j where $j = 1,2,...,J$ consist of G candidate where $\left(G_j \in K\right)$, K is the total number of cognitive users in the network. Then the decision metric for a cooperative group, $M_{c,j}$, can be given by:

$$M_{c,j} = \sum_{g=1}^{G} \sum_{n=0}^{N} s_g[n] \tag{13}$$

The probability distribution of the cooperative group sensing $M_{c,j}$ follows chi-square distribution and by applying the central limit theorem then the statistical nature of metric $M_{c,j}$ under hypothesis H_1, H_0 can be written as:

$$M_{c,j} \big| H_1 \sim N\left(N\left(\sum_{g=1}^{G} \sigma_{x,g}^2 + G\sigma_w^2\right), 2N\left(2\sum_{g=1}^{G} \sigma_{x,g}^2 + G\sigma_w^2\right)\right)$$

$$M_{c,j} \big| H_0 \sim N\left(NG\sigma_w^2, 2NG\sigma_w^2\right) \tag{14}$$

$j = 1, 2, . . ., J$, where J is the number of groups in the network. The detection threshold λ determined by a given P_f and can be estimated as:

$$\lambda_{c,j} = NG\sigma_w^2 + \sqrt{2NG\sigma_x^2} Q^{-1}\left(P_f\right) \tag{15}$$

And the detection probability P_d for the cooperative group sensing can be calculated as:

$$P_{d,j} = Q\left(\left(\lambda_{c,j} - \left(N\left(\sum_{g=1}^{G} \sigma_{x,g}^2 + G\sigma_w^2\right)\right)\right) \Big/ \sqrt{2N\left(2\sum_{g=1}^{G} \sigma_{x,g}^2 + G\sigma_w^2\right)}\right) \tag{16}$$

Then the net probability of detection based on probability of error (BER) can be calculated as

$$P_d = \prod_{j=1}^{J}\left(\left(1 - P_{d,j}\right)\left(1 - \sum_{g=1}^{G_j} \binom{G_j - 1}{g} (-1)^{G_j - g - 1} \left(\frac{G_j}{2\left(G_j - g\right)}\right)\left(1 - \sqrt{\frac{\gamma'_j}{G_j - g + \gamma'_j}}\right)\right)\right)$$

$$+ \left(\sum_{g=1}^{G_j} \binom{G_j - 1}{g} (-1)^{G_j - g - 1} \left(\frac{G_j}{2\left(G_j - g\right)}\right)\left(1 - \sqrt{\frac{\gamma'_j}{G_j - g + \gamma'_j}}\right)\right) P_{d,j} \tag{17}$$

2.3 Node selection

In order to minimize reporting channel bandwidth, we present a reporting scheme that reduces the average number of reporting bits, by allowing only the candidate node with detection information to report its result to fusion node (FN) as illustrated in Fig. 4. Here, if Q exceed the threshold, λ, a reporting decision, R, is taken and binary decision 1 is sent to fusion node otherwise 'no decision' , R', is taken. This is given by:

$$R = \begin{cases} Q < \lambda & R' \\ Q \geq \lambda & R \end{cases} \tag{18}$$

Assume that the FNj receives L out of G_j local decision. If the FNj receives local decision 0 instead of 1, it considered as a reporting error due to imperfect channel and this is auto corrected to 1. The final decision F at the FNj is done based on n. If it receives any local decision 1 or 0 a final decision $F = 1$ is taken. If no local decision is reported, which means no primary user is detected, and then a final decision $F = 0$ is taken. Let $\bar{k}$ denotes normalized average number of reporting bits, $\bar{k} = L_{avg} / G_j$, where L_{avg} is the average number of reporting bits. Let R_L represents the event that there are L cognitive users reporting, and $R'_{G_j - L}$ represent the event that there are $G_j - L$ cognitive users not reporting, then from equations (8, 9) we can write:

$$P\{R_L\} = (P\{Y \geq \lambda\})^L = (1 - P\{Y < \lambda\})^L \tag{19}$$

$$P\{R'_{G_j - L}\} = (P\{Y < \lambda\})^{G_j - L} \tag{20}$$

where $P\{.\}$ is the probability. Further, suppose $P_0 = P\{H_0\}$ and $P_1 = P\{H_1\}$, then the average number of reporting bits is given by:

$$L_{avg} = P_0 \sum_{g=0}^{G_j - 1} k \binom{G_j}{L} P\{R'_{G_j - L} | H_0\} + P_1 \sum_{g=0}^{G_j - 1} k \binom{G_j}{L} P\{R_L | H_1\} \tag{21}$$

R'_0, R'_1 represent probability of 'no decision' $P\{R'\}$ under hypothesis H_0, H_1, respectively, $R'_0 = P\{Y < \lambda | H_0\}$, $R'_1 = P\{Y < \lambda | H_1\}$, then by using equation (20) we can write average number of reporting bits as:

$$\bar{k} = 1 - P_0 R'_0 - P_1 R'_1 \tag{22}$$

From equation (21) it can be shown that the normalized average number of reporting bits $\bar{k}$ is always smaller than 1.

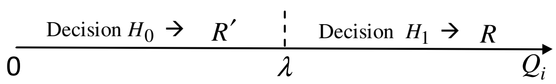
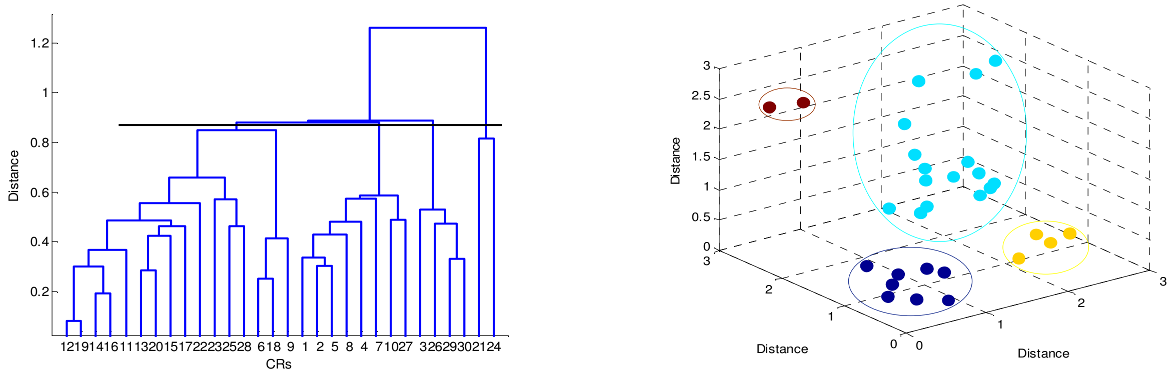


Figure 3. Auto-correction reporting method with one threshold

3. Simulation

The simulation considers cooperative cognitive radios localized in area 3km2, we linked our simulation with the routines in the C clustering library to perform grouping with modified K-Means method where K (or J) is number of groups which set to 4, Fig. 5 illustrates the dendrogram and architecture of node grouping, respectively. The number of users allocated to each group is varying. The channel is considered with physical phenomenon path Loss and multipath. Multipath is modeled as a complex Gaussian random variable, the magnitude of this random variable is Rayleigh [11] and the noise is modeled as AWGN. To maintain probability of false alarm with detection probability, we maintain to have high P_d at P_f around 0.1, in this case the threshold should be set accordingly, $\alpha_{\max}^2, \sigma_w^2\left(\left(\sqrt{2(9+\ln(G_j)} \middle/ \sqrt{N}\right)+1\right)$ for each group where G_j is the number of CR per group.



(a) (b)

Figure 4. (a) Dendrogram of node grouping. (b) Nodes distribution

4. Performance Analysis

Fig. 6-a investigates the ROC (receiver operating characteristics), ($P_{d,j}$ vs. $P_{f,j}$) for the 16 user groups ($G_j = 16$), with different SNR (5, 10 and 15) for the reporting/control channel from the fusion node to fusion centre. The average sensing SNR is 10. The detection threshold is set with maintained probability of false alarm. The results of ROC are only for the group members. It shows that the probability of detection is improved when the threshold is maintained, it can be seen that P_d reach 90% at $P_f = 0.1$ when $\gamma' = 10$ dB for the 16 user group as result of maintained. Analytical results illustrated for $\gamma' = 10$ and it produces comparable performance as simulation.

Fig. 6-b shows the impact of number of nodes within the group, where the figure consider the 2 user group compared to the group with large number of cognitive radios (16 nodes) in Fig. 6 which achieve better performance. Therefore, increasing the number of nodes within the group enhances the detection probability because it may have better distribution that enhances selection diversity. Direct reporting is plotted for each group, it can be confirmed that increasing the number of cooperative users exponentially can obtain gain in detection probability and it is clear that DCS outperforms CS corresponding to the case.

Fig. 7 shows P_d versus sensing SNR γ with different number of sensing groups (1, 2, 3, and 4) under iid Rayleigh fading. The number of user in each group is set as before (2, 4, 8, and 16) distributed based on simulation 'scatter' result shown in Figure 4.1-a with total number of users equal 30 users. For each curve, decision threshold, λ, is chosen such that $P_f = 0.1$. Time-bandwidth product, $m = 5$, and number of samples $N = 16$. Results indicate a significant improvement in terms of required average SNR for detection. Incorporating more groups in sensing enhance detection performance, in particular, for a probability of detection equal to 0.9, one sensing group requires $\gamma = 5.7$ while three sensing group requires $\gamma = 3.3$ to achieve the same probability of detection. Analytical result is plotted for 3 sensing group (J=3, users 2, 4, and 8) and it produces comparable curve. Local spectrum sensing and direct cooperative with 30 users is plotted as well. It can be seen that the DCS with 3 cooperative groups (total of 14 users) outperform the direct reporting. The maintained DCS with $j=3$ requires an average SNR of 3.25 dB for individual users less than direct reporting which require 4.2 dB.

Fig 8 shows the reporting Bit Error Rate (BER) for the proposed method calculated for different number of sensing group. The analytical result is given for 3 sensing group with 2, 4, 8 users. As more number of group incorporated in sensing the probability of error reduced, the results shown that the probability of error in the reporting stage for the same SNR is decreased when number of groups increase. This indicates that the selection of the reporting channel by the mean of fusion node (selection diversity) in the group sensing is achieved. To observe the sensitivity variation; we simulated two sensing group with same reporting SNR, γ' = 10dB. The number of users in these groups was varied and the effect on radio sensitivity for a 90% and 95%, probability of detection was observed. The effect of cooperation on the sensitivity threshold of an individual radio can be seen in Fig. 9 results show an unbounded improvement in threshold as the number of users is increased.

Fig. 10 evaluates the performance in term of bandwidth requirement for control channel. The curves shows that the normalized average reporting bits $\bar{k}$ is decreased and the curve shows that at $P_f = 0.1$ is reduced 42% compared with the conventional method were $\bar{k}$ is always 1, and compared to the two-level quantization or bi-threshold method, discussed in [13]. bi-threshold method produce more reduction as part of the of nodes with or without detection result are eliminated from reporting their decision, however, this method creates a loss in the probability of false alarm due to the large 'no decision region', additionally this scheme may eliminate a user with real detection information from reporting the decision which increase probability of interference to primary system.

5. Conclusion

The main focus of this chapter was to examine the effects of distributed decision fusion based on maintained probability of false alarm and best reporting channel selection on the cooperative spectrum sensing employed by cognitive radios. The simulation results have highlighted that DCS schemes can improve network performance in terms of probability of detection, probability of error, control overhead, sensitivity requirement as well as overall throughput.

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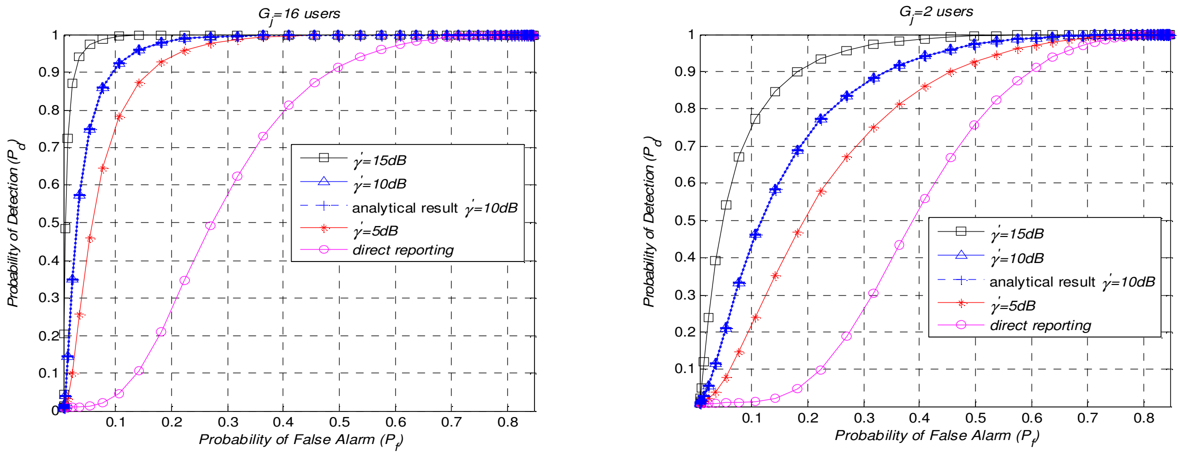

(a) (b)

Figure 5. ROC ($P_{d,j}$ vs. $P_{f,j}$) for different reporting channel SNR. (a) $G_j = 16$ (b) $G_j = 2$

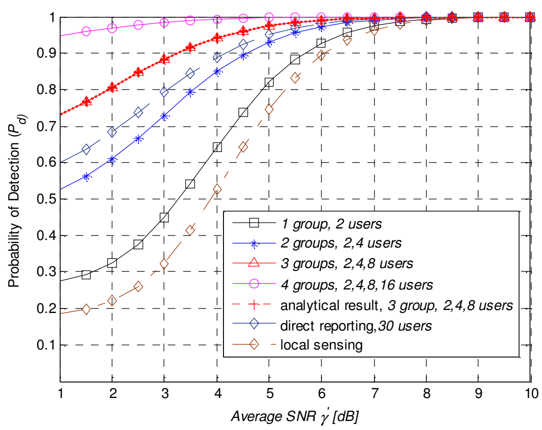

Figure 6. P_d vs. γ under iid Rayleigh fading for different number of cooperative groups ($P_f = 0.1$, m = 5, n = 2)

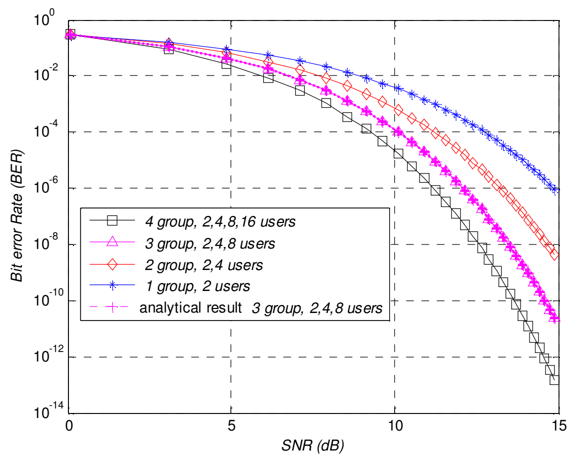

Figure 7. BER for DCS with different number of sensing groups

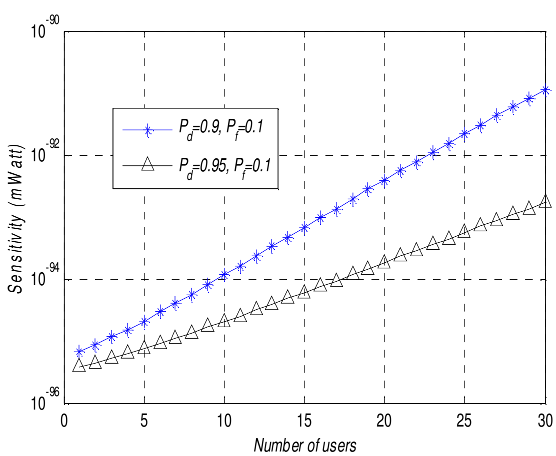

Figure 8. Sensitivity variation with number of users (P_f =0.1)

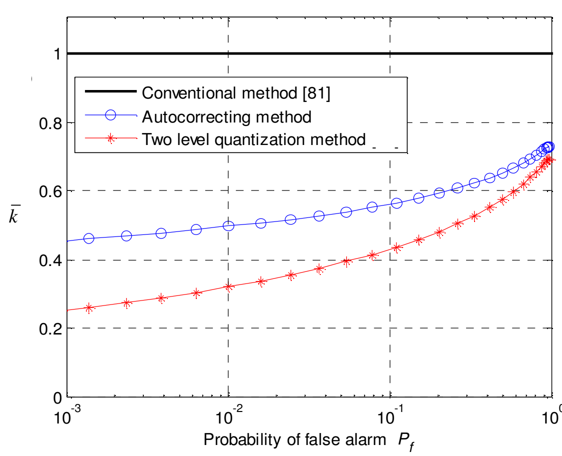

Figure 9. The normalized average number of sensing bits P_f vs. $\bar{k}$, (SNR $\gamma = 10$ dB, $P_d = 0.9$)

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