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Cluster based distributed CSS has been compared with the centralized CSS. Various decision fusion strategies have been discussed and analyzed. Effects of fusion rules, no. of cognitive radio users, sensing channel SNR and diversity on detection performance have been illustrated over various fading channels.
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Girraj Sharma¹ and Ritu Sharma¹*

Abstract: Spectrum sensing is the important aspect of cognitive radio (CR). In order to use the vacant spectrum, cognitive radio user must be able to identify the presence of empty spectrum efficiently. A non-cooperative spectrum sensing faces the problem of shadowing and hidden terminal due to which the CR user fails to monitor the vacant spectrum. To solve the problem of hidden terminal and shadowing in non-cooperative spectrum sensing, cooperative spectrum sensing (CSS) is used. CSS can be divided in two categories, centralised and distributed. In this paper comparison of centralised and distributed CSS is presented and a cluster based distributed CSS is proposed over fading channel with different fusion rules and effect of number of CR users and number of clusters on the performance has been investigated. It is investigated that if number of users and number of cluster increases, user cooperation increases and chances of detection of empty spectrum increases. Detection probability increases 134% for SNR = 0 dB when total number of CR users in a cluster is fixed at 2 and number of clusters are varied from 2 to 8 and it increases 97% when total number of clusters are 3 and number of CR users in a cluster is varied from 2 to 8.

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PUBLIC INTEREST STATEMENT
Cognitive radio allows unlicensed users also known as a secondary user (SU) to operate in the licensed band. It can solve the problem of spectrum underutilization in the wireless communication. The licensed users known as primary user (PUs) have higher priority to use the spectrum than SUs. The SU should be able to identify the presence of vacant spectrum through spectrum sensing. This spectrum sensing can be performed by individual SUs known as non-cooperative spectrum sensing or it can be conducted by a group of SUs which performs spectrum sensing by collaboration known as cooperative spectrum sensing.

The research work in above field helps to solve the problem of spectrum scarcity in wireless communication. In present scenario there is a lot of heavy traffic in some wireless applications and in some wireless application there is less traffic so we need dynamic spectrum utilization instead of static spectrum utilization. Cognitive radio is such technique which can provide dynamic spectrum allocation in wireless communication.
1. Introduction
Cognitive radio allows unlicensed users also known as a secondary user (SU) to operate in the licensed band. It can solve the problem of spectrum underutilization in the wireless communication. The licensed users known as primary user (PUs) has higher priority to use the spectrum than SUs. The SU should be able to identify the presence of vacant spectrum through spectrum sensing. This spectrum sensing can be performed by individual SUs known as non-cooperative spectrum sensing or it can be conducted by a group of SUs which performs spectrum sensing by collaboration known as cooperative spectrum sensing.

A lot of literature is available to improve the performance of CSS (Kanti & Tomar, 2017; Zhang, Mallik, & Letaief, 2009; Zhang, Wu, Lu, & Iyengar, 2012). Under imperfect reporting channel, performance of CSS was improved by introducing CR censoring method (Bhowmick, Nallagonda, Roy, & Kundu, 2015; Nallagonda, Roy, & Kundu, 2013). In Nallagonda et al. (2013) a weight based censoring method was introduced in CSS, in which only the SUs which have highest reporting channel coefficient were selected to transmit data. In Bhowmick et al. (2015) double threshold energy detection was used to improve the performance of CSS. Hybrid censor method is used in Bhowmick, Roy, and Kundu (2015) where combination of soft fusion and hard fusion rule is applied. Double dynamic threshold method is proposed (Farag & Mohamed, 2015) for soft and hard CSS to reduce the effect of noise uncertainty in sensing channel. A cluster based CSS approach was suggested in Pratas, Marchetti, Parsad, Rodrigues, and Parsad (2010). In this method, the cluster head regulates the distribution of the sensing node. In Lo & Akyildiz (2010) a decentralised CSS was proposed in which channel is sensed by the node based on past sensing results. A full distributed CSS was introduced in Yu, Huang, and Tang (2010) where spectrum sensing based on biology is suggested in which consensus are used to make final decision. CSS over fading channels is studied in Al Hammadi et al. (2016), Lau, Yue, and Wang (2012), Reisi, Gazor, and Ahmadian (2013), and Vien, Nguyen, Trestian, Shah, and Gemikonakli (2016). In Vien et al. (2016) a hybrid double threshold based CSS is discussed over fading channels. For this a hybrid double threshold based energy detector is proposed to improve the performance and to reduce the number of forwarding bits for a lower complexity signalling. Performance of CSS with low SNR over fading channel is studied in Lau et al. (2012) in which a multiuser cooperative scheme is proposed, inspired by the cluster based CSS. In Al Hammadi et al. (2016) performance of CSS with multiple antenna nodes over generalised and composite fading channels is investigated. Authors also discussed diversity combining techniques in Al Hammadi et al. (2016) to mitigate the effect of multipath fading and shadowing. Distributed CSS in mixture of large and small scale fading channels is investigated in Reisi et al. (2013), where the PU signal is assumed as random and deterministic signal with known power and the channels random with Nakagami lognormal mixture distribution. None of the literature is available which compares the performance of distributed CSS over Rayleigh, Nakagami and Rician fading channel with respect to parameters reported in this paper thus this analytical study becomes relevant and helps in deciding the type of channel to be used under fading conditions. Centralised CSS with noisy reporting channel has been reported in Sharma and Sharma (2016) which reports the detection performance of centralised CSS when reporting channel is not ideal. In this paper work is extended over various fading channels for distributed CSS.

Based on above literature a cluster based distributed CSS over fading channel is proposed in this paper. Clustering can (a) provide better local spectrum information, (b) provide better resource allocation (c) provide network scalability (d) be more energy efficient (Joshi & Kim, 2016). Although due to clustering system becomes complex but there is a significant improvement in detection performance. So while designing any network a trade-off is there between performance and
complexity. Most of the papers above discussed centralised CSS over Rayleigh fading. In this paper performance of distributed CSS is compared over Rayleigh, Nakagami and Rician fading channels. Nakagami fading is generalized distribution which can model different fading environments, also Rayleigh and one-sided Gaussian distribution are special cases of Nakagami-m model. Rician distribution suits better in sub-urban areas where LOS components exist. Distributed CSS is economical then centralised CSS as there is no base station required in it.

2. System model

2.1. Centralised cooperative spectrum sensing

If there are \( K \) number of CR users and single PU with a common fusion centre which manages the CR network, then each SU detects the presence of PU using energy detector (ED). In an energy detector signal \( x(t) \) is given as input and it gives an output which is in the form of binary decision with reference to presence of PU. For jth CR in the network. There are following two hypotheses:

\[
Z_j(t) = \begin{cases} 
  w_j(t), & H_0 \\
  h_j x(t) + w_j(t), & H_1 
\end{cases}
\]

where \( Z_j(t) \) is the signal received at the jth CR, \( x(t) \) is the transmitted signal from the PU, \( w_j(t) \) is the gaussian noise, and \( h_j \) is the complex gain of the channel. Based on the system model in (1), we have the \( |E_j| \) i.e. the computed energy received, the Signal-to-Noise Ratio (SNR) at the CR, i.e. \( \Upsilon_j \), and the time bandwidth product \( u \). The PU signal is detected by comparing the energy \( |E_j| \) with a threshold value \( \lambda_j \). Therefore, the false alarm probability is given by

\[
P_f(j) = Pr(|E_j| > \lambda_j | H_1) = \frac{\Gamma(u, \frac{\lambda_j}{2})}{\Gamma(u)} \tag{2}
\]

and the detection probability is given by

\[
P_d(j) = Pr(|E_j| > \lambda_j | H_0) = Q(\sqrt{2\Upsilon_j}, \sqrt{\lambda}) \tag{3}
\]

\[
P_m(j) = 1 - P_d(j) \tag{4}
\]

Average probability of detection under fading scenario can be calculated by averaging Equation (3) i.e.

\[
P_d = \int_0^\infty Q(\sqrt{2\Upsilon}, \sqrt{\lambda})f(\Upsilon)d\Upsilon \tag{5}
\]

where \( f(\Upsilon) \) is the probability density function (PDF) of \( \Upsilon \) under fading.

In centralised CSS, all CR users detect the availability of the vacant spectrum individually. After performing local spectrum sensing each SU makes a binary decision and then forward decision to the fusion centre. Let \( S_j \in \{0, 1\} \) denote the independent local sensing result of the jth CR. Where \( [0] \) indicates presence of vacant spectrum and \( [1] \) indicates the absence of the vacant spectrum. At the fusion centre, decisions are fused together according to the following logic rule

\[
Y = \sum_{j=1}^{K} S_j \begin{cases} 
  \geq i, & H_1 \\
  < i, & H_0 
\end{cases}
\]

Here \( i = 1 \) corresponds to OR rule and \( i = K \) corresponds to AND rule. Based on (6), False alarm and miss detection probability of centralised CSS for OR and for AND rule is given by

\[
Q_f^{0r} = 1 - \prod_{j=1}^{K} (1 - P_f(j)) \tag{7}
\]
where \( P_{f}^{(j)} \) denotes the probability of false alarm and \( P_{m}^{(j)} \) denotes the probability of miss detection of the \( j \)th CR user given in Equations (2) and (3) respectively.

2.2. Distributed CSS

In distributed CSS there is no common Fusion centre. Each SU will perform spectrum sensing individually then this information is transmitted to the other SUs to decide on mutual probability of presence of PU. In Figure 1(a) a distributed CSS with 6 CR users and 1 PU is illustrated.

2.2.1. Cluster based distributed CSS

In cluster based distributed CSS each SU will perform the local spectrum sensing then this information will be exchanged between the other SUs of same cluster by some fusion rule to decide the presence of primary user. Thus each cluster has its final decision of presence of PU. This information exchanges between clusters through the cluster heads (CH), which is responsible for data collection, information circulation and network management (Joshi & Kim, 2016). Non cluster heads are responsible mainly for sensing and collecting information from surroundings. The CH provides scalability for large network and reduces the energy consumption. If there are large number of nodes in the network than large number of CH is required which can communicate with base station using long distance transmission. On the other hand if number of nodes is small than in a cluster of big diameter large amount of energy is consumed to send data from node to CH. So a trade-off should be made between these two scenarios.

\[
Q_{m}^{or} = \prod_{j=1}^{K} P_{m}^{(j)}
\]  

(8)

\[
Q_{f}^{and} = \prod_{j=1}^{K} (P_{f}^{(j)})
\]  

(9)

\[
Q_{d}^{and} = \prod_{j=1}^{K} P_{d}^{(j)}
\]  

(10)

\[
Q_{m}^{and} = 1 - Q_{d}^{and}
\]  

(11)

Figure 1. (a) Distributed CSS, (b) Cluster based distributed CSS.
Clustering is also defined as the activity of creating sets of similar objects. In a clustered wireless sensor network, nodes can be classified as primary nodes and secondary nodes. Primary nodes performs the task of data aggregation and processing and secondary nodes performs data forwarding only.

In cluster based CSS, CH can be selected randomly or based on one or many criteria. An ideal CH is one which has smallest distance from base station, maximum number of neighbouring nodes and highest residual energy. Considering all these criteria simultaneously is difficult task. It can be solved by using multiple attribute decision-making approaches like low energy adaptive cluster hierarchy (LEACH), Distributed hierarchical agglomerative clustering (DHAC), hybrid energy-efficient distributed protocol (HEED) etc.

The clustering algorithms can be classified in three categories: centralized clustering, distributed clustering and hybrid clustering. In centralized clustering, cluster head is fixed but in distributed clustering, cluster head is not fixed. The CH location changes from node to node based on some parameters. In hybrid clustering features of both centralised and distributed clustering is included. In this study centralised clustering approach is used in which CH is fixed.

There are four fusion possible for this cluster based CSS as follows:

2.2.1.1. **OR-OR fusion.** Each individual secondary user in a cluster identify the vacant spectrum by local sensing then it will fuse its information with the other members of the cluster with OR fusion. Subsequently each cluster also fuse the information with other clusters with OR fusion. In Figure 1(b), a cluster based distributed CSS is explained. There are three clusters C1, C2 and C3 in the system and each cluster has three member in it. Each cluster has one CH, which exchange the information with other CH. CR users in the cluster will exchange information using OR fusion and clusters C1, C2, C3 will also share their decision with OR fusion.

The probability of false alarm and miss detection of distributed CSS for OR-OR rule is derived from centralised CSS and is given by

\[
Q_f^{\text{or-or}} = 1 - \prod_{j=1}^{l} \left( 1 - Q_f^{\text{or}(j)} \right) \tag{12}
\]

\[
Q_m^{\text{or-or}} = \prod_{j=1}^{l} Q_m^{\text{or}(j)} \tag{13}
\]

Where \( j \) is the number of CR users in a Cluster and \( l \) is the total no of clusters.

2.2.1.2. **OR-AND fusion.** The CR users will exchange information using OR fusion and clusters will share their decision with AND fusion. The false alarm and detection probabilities of distributed CSS for OR-AND rule derived from centralised CSS is given by:

\[
Q_f^{\text{or-and}} = \prod_{j=1}^{l} \left( Q_f^{\text{or}(j)} \right) \tag{14}
\]

\[
Q_d^{\text{or-and}} = \prod_{j=1}^{l} Q_d^{\text{or}(j)} \tag{15}
\]

2.2.1.3. **AND-OR fusion.** The CR users will exchange information using AND fusion and clusters will share their decision with OR fusion. The false alarm and miss detection probability of distributed CSS for AND-OR rule derived from centralised CSS is given by:
2.2.1.4. **AND-AND fusion.** The CR users will exchange information using AND fusion and clusters will also share their decision with AND fusion. False alarm and detection probability of distributed CSS for AND-AND rule derived from centralised CSS and is given by:

\[
Q_{f}^{\text{and-and}} = 1 - \prod_{j=1}^{I} \left( 1 - Q_{f}^{\text{and}j} \right) \\
Q_{m}^{\text{and-and}} = \prod_{j=1}^{I} Q_{m}^{\text{and}j} \\
\]

3. **Fading channel distributions**

3.1. **Rayleigh fading channel**

If the received signal amplitude following the Rayleigh distribution, the SNR distribution can be formulated according to Nallagonda et al. (2016)

\[
f_{1}(\Upsilon) = \frac{1}{\Upsilon} \exp \left( -\frac{\Upsilon}{2} \right); \quad \Upsilon \geq 0
\]

We can calculate probability of detection \( \bar{P}_{d}^{\text{ray}} \) by substituting Equation (20) in Equation (5), i.e.

\[
\bar{P}_{d}^{\text{ray}} = \frac{1}{1 + \bar{\Upsilon}} \sum_{n=1}^{\bar{\Upsilon}} \left( \frac{\lambda}{2} \right)^{n} \exp \left( -\frac{\Upsilon}{2} \right) \frac{\exp \left( -\frac{\Upsilon}{2} \right)}{n!} 1F1 \left[ 1; n + 1; \frac{\bar{\Upsilon} \lambda}{2(1 + \bar{\Upsilon})} \right] + \exp \left[ -\frac{\lambda}{2(1 + \bar{\Upsilon})} \right]
\]

where \( 1F1 \) \((; ; ;)\) denotes confluent hypergeometric function.

3.2. **Nakagami fading channel**

If the received signal amplitude following the Nakagami distribution, the SNR distribution can be formulated according to Nallagonda et al. (2016)

\[
f_{1}(\Upsilon) = \left( \frac{m}{\Upsilon} \right)^{m-1} \frac{\exp \left( -\frac{m \Upsilon}{m + \Upsilon} \right)}{\Gamma(m)} ; \quad \Upsilon \geq 0
\]

where \( m \) is a constant known as the fading parameter for nakagami channel.

We can calculate probability of detection \( \bar{P}_{d}^{\text{nak}} \) for nakagami distribution by substituting Equation (22) in Equation (5), i.e.

\[
\bar{P}_{d}^{\text{nak}} = \left( \frac{m}{m + \bar{\Upsilon}} \right) \sum_{n=1}^{\bar{\Upsilon}} \left( \frac{\lambda}{2} \right)^{n} \frac{\exp \left( -\frac{\Upsilon}{2} \right)}{n!} 1F1 \left[ 1; m + n + 1; \frac{\bar{\Upsilon} \lambda}{2(m + \bar{\Upsilon})} \right] + \\
\left( \frac{\bar{\Upsilon}}{m + \bar{\Upsilon}} \right) \exp \left[ -\frac{2m \bar{\Upsilon}}{2(m + \bar{\Upsilon})} \right] \times \left\{ \sum_{k=0}^{m-1} \left( \frac{m}{m + \bar{\Upsilon}} \right)^{k} L_{k} \left[ -\frac{\bar{\Upsilon} \lambda}{2(m + \bar{\Upsilon})} \right] + \left( \frac{m + \bar{\Upsilon}}{\bar{\Upsilon}} \right)^{m-1} L_{m-1} \left[ -\frac{\bar{\Upsilon} \lambda}{2(m + \bar{\Upsilon})} \right] \right\}
\]

where \( L_{k} \) \((; ; ;)\) is the Laguerre polynomial of degree \( r \).
3.3. Rician fading channel

For Rician distribution the PDF of random variable $\Upsilon$ is given by Nallagonda et al. (2016)

$$f_\Upsilon(\Upsilon) = \frac{1 + k}{\Upsilon} \exp\left[-k - \left(\frac{1 + k}{\Upsilon}\right)\right] I_0(2 \sqrt{\frac{k(1 + k)}{\Upsilon}}); \Upsilon \geq 0$$  \hspace{1cm} (24)

where $k$ is a constant known as the Rician parameter defined as the ratio of the power in the dominant component and the power in the scattered path and $I_n(.)$ is nth order Bessel function of first kind.

The average probability of detection $\overline{P}_{d_{\text{ric}}}$ can be calculated by substituting Equation (24) in Equation (5), i.e.

$$\overline{P}_{d_{\text{ric}}} = \frac{1 + k}{\Upsilon} \exp(-k) \sum_{n=0}^{\infty} \frac{\Gamma(\overline{\Upsilon} + n, \frac{k}{2})}{\Gamma(\overline{\Upsilon} + n)} \left(\frac{\Upsilon}{1 + k + \Upsilon}\right)^{n+1} \times 1F1\left[n + 1; 1; \frac{k(1 + k)}{1 + k + \Upsilon}\right]$$ \hspace{1cm} (25)

Rayleigh distribution is the most used signal model in wireless communications because it represents the worst fading case. Nakagami fading is generalized distribution which can model different fading environments, also Rayleigh ($m = 1$) and one-sided Gaussian distribution ($m = 1/2$) are special cases of Nakagami-m model. Rician distribution suits better in sub-urban areas where LOS components exist. Rician parameter $k = 0$, represents Rayleigh distribution.

4. Numerical results

The performance analysis of spectrum sensing with fusion rules described in Section 2 is made assuming the perfect report channels between the fusion centre and secondary users. The number of cluster and users within a cluster is equal to two (2), in order to keep the simplified design model. Later in this section it is observed that if number of cluster and number of user increases, detection performance also increases, however sensing time also increases which is not considered in the reported work and is also an area of research interest.

In Figures 2 and 3 probability of detection is plotted against SNR for centralised and distributed CSS over Rayleigh fading channels and Nakagami fading channels ($m = 3$) for time bandwidth product ($u$) = 1 and average SNR ($\Upsilon$) is varied.
Figure 2 shows the comparison of centralised and distributed CSS for different values of SNR. From Figure 2 it can be observed that in distributed OR-OR fusion we require SNR less than 10 dB to attain probability of detection of 0.9. Whereas in other fusion schemes we require SNR more than 10 dB to attain 0.9 $P_d$ because in OR-OR fusion rule, if at least one SU or one cluster has local decision of PU presence than FC indicates presence of PU. The performance of cluster based distributed CSS for OR-OR fusion is better than centralised CSS for OR fusion because user cooperation increases in cluster based approach and hence detection performance increases.

It can be observed from Figure 3 that probability of detection over Nakagami fading channel is greater than Rayleigh fading channel. The slope of the $P_d$ vs. SNR curve is steeper over Nakagami channel compared to Rayleigh channel because for $m > 1$, the fluctuations of the signal strength reduces compared to Rayleigh fading.
Figure 4 shows the Pd vs. SNR plot for Rician Fading distribution for Rician factor $k = 3$. It can be observed from Figure 4 that performance over Rician fading is similar to Nakagami fading and better compared to Rayleigh fading.

Figure 5 illustrates complimentary ROC curves for OR-OR fusion over Nakagami, Rician and Rayleigh fading channels. Rician $k = 0$ and Nakagami $m = 1$ curves coincide with Rayleigh curve and therefore not shown here. Clearly performance improvement is observed for $m$, 2 to 4 and $k$, 1 to 2. The Rician fading constant $k$ is the ratio of power in direct path and scattered paths. Larger values of $k$ gives better performance as we can see in Figure 5, performance improves as Rician fading constant increases.

Figures 6 and 7 shows Pd vs. SNR plot of cooperative CSS with OR-OR fusion over Rayleigh fading channel with different number of CR users in a cluster and different number of clusters. Clearly the
greater is the number of clusters or number of secondary users in the cluster, the higher performance can the network achieve. In Figure 6 total number of CR users in a cluster is 2 and number of clusters are varied. In Figure 7 total number of clusters are 3 and number of CR users in a cluster is varied.

It can be observed from Figures 6 and 7 that probability of detection increases in both the cases as total number of CR users or total number of clusters increases. If number of CR users and number of clusters increases, user cooperation increases and chances of detection of empty spectrum increases. However with the increase of both \( L \) and \( N \), energy consumption and overhead of the network increases.

5. Conclusion
In this paper, the performance of centralised and distributed cooperative spectrum sensing is compared over different fading channels. Centralised CSS has been discussed with two fusion rules and distributed CSS is discussed with four different fusion rules. The results show that distributed OR-OR fusion outperforms the other fusion rules and in centralised CSS, OR fusion rule gives better performance. It is also found that if the number of clusters are increased then probability of detection also increases. Also performance gets improved when number of secondary users in a cluster is increased because large number of secondary users can effectively detect the presence of primary users however it will increase the sensing duration.

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