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SUB-SPECTRUM SENSING BASED ON REPUTATION IN CRNS

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Abstract. *As an intelligent wireless network, cognitive radio network has the ability of spectrum sensing, adaptive spectrum allocation and wireless spectrum management, but there are still some serious problems such as low sensing efficiency and security issues. To increase the efficiency of spectrum sensing and ensure the fairness and accuracy in sensing progress, we propose a sub-spectrum sensing scheme based on reputation. After that we extend the reputation in the scheme proposed to the spectrum allocation process. The simulation shows that our scheme can defense Spectrum Sensing Data Falsification (SSDF) attacks effectively, and increase the efficiency and fairness of the spectrum sensing.*

Keywords: Spectrum sensing, Data fusion, Reputation

1. **Introduction.** With the increasing demand for wireless communication, traditional static spectrum allocation has become more constrained, which leads to the concern about the cognitive radio technology. As the specific spectrum sensing function, cognitive radio accesses free license by dynamic access technology opportunistically to enhance the spectrum utilization.

One of the key technologies to increase the efficiency of spectrum usage is cognitive radio technology, which can sense the environment and make the map of spectrum using, and access the white holes by dynamic spectrum access, thus to improve spectrum utilization.

Rapidly detecting white holes and information of primary users is one technology which is the premise of cognitive radio. The challenge of spectrum sensing is how to design a reliable sensing algorithm. There are three kinds of sensing technologies available: energy detection, cyclostationary feature detection, matched filtering, but they are all sensing by analyzing signal characteristics and causing many problems. On this basis, cooperative sensing [1-3] has been proposed that all cognitive users make the primary user information by multi-node cooperation mechanism. The idea of cooperative sensing was first proposed by A. Ghasemi to solve Hidden terminal problem in [4]. Researchers have proposed a security framework for cognitive radio IP based cooperative protocols [5] and a supervising authenticated encryption scheme [6], which can assure mutual authentication, confidentiality and integrity. To optimize cooperative sensing efficiency, H. N. Pham presented a scheme to minimize energy consumption. Besides, the security problems during sensing cannot be neglected. To encourage users to send accurate data and punish malicious users, K. Zeng proposed a reputation-based cooperative spectrum sensing scheme with trusted nodes assistance [7]; only when the reputation value is within trust value, can the user participate in the collaborative sensing. An optimized cooperative sensing scheme was presented in [8], and N.-T. Nhan proposed a cooperative spectrum sensing

using enhanced Dempster-Shafer Theory of evidence in [9], which utilized the signal to noise ratios to evaluate the degree of reliability of each local spectrum sensing terminal on a distributed cognitive radio network to adjust the sensing data more accurately before making fusion by Dempster-Shafer Theory of evidence. Compared with the previous algorithm, this scheme can improve accuracy of sensing and do better than "and" and "or" decision fusion rules. But in all the schemes, users sense randomly and this can bring huge overhead. A scheme for dynamic compressive spectrum sensing was proposed by W. Yin and the analysis shows its fast speed and robustness to noise [10]. But once there exists cheating partner, the scheme may cause two following results. One is that the cheating partner occupies the free channel which is a white hole all the time to make unfair communication; the other one is that this could interfere with the primary users. F. Zeng and Z. Tian proposed a cooperative approach to wideband spectrum sensing, which divided the entire wideband spectrum into M non-overlapping narrowband subchannels [11]. They adopted compressive sampling mechanism and collected local data to reach the global consensus optimization. But the exchanged information must percolate over the network through multiple rounds to reach global convergence, and it causes longer time delay. In dynamic wireless environment, too long time delay [12] will result in the interference with primary networks.

Cooperative sensing can avoid hidden terminal problems and make spectrum sensing data more accurate, but it also causes security problems such as cheating partner, which is one type of spectrum sensing data falsification (SSDF) attacks [13]. Multiple users collaborate to do malicious behaviors to achieve their goals. Meanwhile, massive data processing due to random sensing will increase the decision time of fusion center and the simple cognitive competition mechanism cannot motivate users to sense. In addition, though diffusion mechanism may reach the global convergence, it also increases the time delay.

For the problems existing in cooperative sensing, it is urgent to improve sensing efficiency, reduce the probability of cheating partner, minimize the cost of each user and make the sensing data more accurate.

In this paper, we propose a sub-spectrum sensing scheme based on reputation, and there are two main contributions. First, by dividing the spectrum bands, we assign each user to sense corresponding bands to increase sensing efficiency. The cooperative sensing schemes available are all sensing schemes which use the data from all cognitive users randomly, and this may lead to serious consequences, such as concentration of certain frequency bands, non-user sensing bands, so the fusion center cannot receive the integrity information and maximize the use of spectrum holes that all these maybe waste resources. Second, dividing cognitive users and considering the reputation to networks can prevent attacks on cheating partner to reduce the impact of SSDF attacks. Cognitive users are divided into different groups according to IDs when joining in network, and each group has different tasks of sensing. Fusion center makes final decision by the data from cognitive users with the reputation of each user, and feedback the results to update the users' reputation. Then after updating reputations we can detect malicious users and remove them to assure the security of cognitive radio networks.

The rest of the paper is organized as follows. In Section 2, we describe spectrum sensing process and propose a sub-spectrum sensing scheme based on reputation. Section 3 is the model solution. We analyze the model in Section 4 in detail and conclude the paper in Section 5.

2. **Spectrum Sensing.** Spectrum sensing is one of the key technologies in cognitive radio networks. Accurately detecting spectrum holes is a precondition for full use of

spectrum. We should allocate resources without affecting primary users to maximize spectrum efficiency.

2.1. **System model.** Real-time spectrum sensing to obtain primary information is a precondition for realization of cognitive radio. Since the cooperative sensing schemes available are all sensing randomly and cannot defense cheating partner. Besides, to deal with massive data without any filter is a bottleneck to fusion center and may result in false decision.

For the problems above, we design a scheme to let users sense part of bands instead of all bands randomly. In our scheme, we use the hybrid model. We adopt Identity-based validation techniques at the network initialization. At the time joining the work, users register to get the unique identity (ID) and random key. A central authority validates each user when communicating and reputation updating. After registration, all the cognitive users have been distributed in the perception within the network structure. Cluster head has already elected according to reputation value. Each cognitive user sends sensing information to cluster head directly for processing to get the final decision as Figure 1.

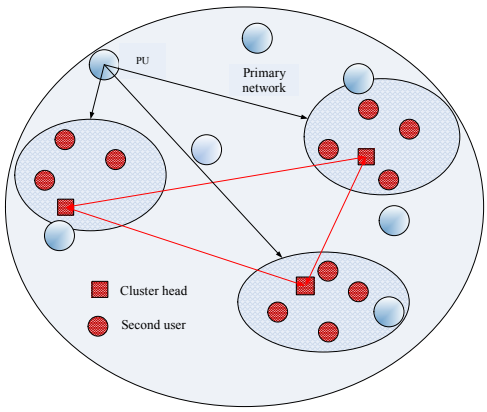

FIGURE 1. Structure of spectrum sensing in cognitive radio

Assumptions:
1) The set of limited spectrum to be sensed should maintain relatively stable;
2) Each cluster has the same number of cognitive user groups;
3) Cognitive users add to cluster according to their location, and cluster heads which have been elected already are reliable;
4) The cost of the same band for each user is equivalent;
5) Each CR user is equipped with an adjustable omnidirectional antenna and the table of symbols and definitions in our model is showed in Table 1.
Model:

To ensure the accuracy of sensing data and defense cheating partner effectively with minimal overhead in a relatively stable sensing spectrum set, we propose a model in the

TABLE 1. Symbols and definitions

Symbols	*Definitions*
$f_i(x)$	User numbers sensing the same band i
$N_i(x)$	Unit sensing cost
P_j	Probability of cheating partner
P_{MD}	Probability of miss detection
G_i	The ith group
n	Number of users
$S_i{}'$	The ith set of bands
N	Number of groups

following:

$$\begin{cases} \max \sum_{i=1}^{N} f_i(x) \\ \min \sum_{i=1}^{N} f_i(x) N_i(x) \\ \\ \text{s.t.} \\ P_{MD} \leq \delta \\ P_j \leq c. \quad j = 1, 2, \ldots, m \end{cases} \tag{1}$$

where $f_i(x)$ is the number of groups in which users sensing the same bands; $\sum_{i=1}^{N} f_i(x) N_i(x)$ is the sensing cost; P_j is the probability of cheating partner; c is a constant and m is the number of clusters; P_{MD} is the probability of miss detection and δ is the tolerance of primary user. To limit P_j within a certain condition, we should minimize sensing cost as possible.

In a particular environment, the system designer will always have a special request. For example, strong security requirements, as little as possible cost and so on. The goal of cognitive radio network is to maximize spectrum usage with minimal overhead. In order to improve the accuracy of sensing data, one method is letting more users sense the same band, but this can cause much more cost. So we should find out a trade-off point to meet scene needs.

2.2. **Algorithm.** The step is as follows:

a. User group

Taking all the users into several clusters according to geographical location, and each cluster has n users represented by $U_1, U_2, \ldots, U_n$, we divide the n users into N groups $G_1, G_2, \ldots, G_N$, the G_i $(1 \leq i \leq N)$ is called user group. With the users' ID number assigned which is located when joining the cluster, we take u_i into group G_j, $j \equiv i \bmod (N)$.

b. Band division

The set of all the bands need to be sensed is S, $S = [S_1, S_2, \ldots, S_K]$. We take S into N groups, every $\lceil K/N \rceil$ bands are bound together to form a new set $[S_1{}', S_2{}', \ldots, S_N{}']$, where $S_i{}'$ $(1 \leq i \leq N)$ contains $\lceil K/N \rceil$ bands, $K > N$. If $K = 0 (\bmod N)$, there are K/N bands in $S_i{}'$; else, $K \neq 0 (\bmod N)$, we let the rest bands be a group. The set of

bands meet the following conditions:

$$\begin{cases} S_i' \cap S_j' = \emptyset \\ S_1' \cup S_2' \cup \ldots \cup S_i' \cup \ldots \cup S_N' = S \\ 1 \le i, \quad j \le N, \quad i \ne j \end{cases} \tag{2}$$

c. Sub-spectrum sensing

A cluster, for example, a collection algorithm of all the bands assigned to the users within the group is as follows:

1) First, the initial allocation

Assign $S_1', S_2', \ldots, S_N'$ randomly into user groups $G_1, G_2, \ldots, G_N$ and make sure each G_j corresponds with one S_i' uniquely, where $i, j \in (1, 2, \ldots, N)$;

2) Second distribution

If $S_i' \in G_j$, copy S_i' and then take it into another group G_l, $j, l \in (1, \ldots, N)$, $l \ne j$;

3) Third distribution

$S_i' \in G_j, S_i' \in G_l$, copy S_i' then take it into group G_m, $j, l, m \in (1, \ldots, N)$, $l \ne j \ne m$;

4) Continue to distribute until the kth;

5) To ensure the same bands bound cannot be placed in the same three groups;

6) If N_p, the bands number of user group G_p reaches 3, then G_p is full or cannot be placed in this group;

7) For all the other S_j', do 1), 2), 3), 4), $1 \le j \le N$, $j \ne i$.

With the distribution above, users of each cluster begin sensing the bands in the group they assigned into. Each cognitive user adjusts its antenna to the bands assigned and transmits the sensing data to cluster head; then cluster head makes decision refer to users' reputation according to information received and negotiates the result with other neighbor cluster heads to make final decision.

First, we define the calculation of reputation value. Assume that the network has N cognitive users, $d_i^m(t)$ represents the judgment of the ith cognitive user for band m, and $d^m(t)$ is the final judgment by cluster heads at time t.

$$d_i^m(t) = \begin{cases} 0, & \text{no primary user signal in band } m \\ 1, & \text{else} \end{cases} \tag{3}$$

The calculation of reputation value of cognitive radio is as follows:

Initialization: All the new users join the network with the reputation value 0;

Reputation value: The reputation of the ith user in time t is:

$$r_i(t) = \begin{cases} 0, & t = 0 \\ \mu r_i(t-1) + (-1)^{d^m(t) + d_i^m(t)}, & t > 0 \end{cases} \tag{4}$$

where μ is a decay factor, a constant in $(0, 1)$. When user is inactive over a certain time limit, $r_i(t) = \mu r_i(t-1)$. According to the data information cognitive users upload, the data fusion center makes final judgment for band m:

$$d^m(t) = \begin{cases} 0 & D^m(t) \ge \lambda \\ 1 & \text{else} \end{cases} \tag{5}$$

$$D^m(t) = \sum_i \omega_i(t) {d_i}^m(t) \tag{6}$$

where the user i is in the partition contains band m. $d^m(t)$ is the final sensing result judged by fusion center. According to the comparing of $d^m(t)$ and $d_i^m(t)$, we can update the ith user's reputation value with Formula (4). $\omega_i(t)$ is a monotone increasing function

of $r_i(t-1)$.

$$\omega_i(t) = \frac{\omega_i{}^*(t)}{\sum_{j=1}^{N} \omega_j{}^*(t)} \tag{7}$$

$$\omega_i{}^*(t) = \frac{r_i(t-1)}{\max_{j=1,2,\ldots,N}(r_j(t-1))} \tag{8}$$

If the reputation value of a cognitive user is out of the trust range, we can consider the cognitive user as malicious user, and withdraw it from the network.

Each cluster head updates the reputation of cognitive users within cluster after the feedback of fusion center and the reputation of cluster head is updated by fusion center. The reputation table will be open in the network. According to cooperative interaction, each user records the reputation of neighbor nodes for future collaboration. In our scheme, we use soft decision inside cluster and hard decision between clusters. This is because soft decision is more suitable for a cluster in similar environment and hard decision is much more quickly to make final decision for fusion center. This can decrease time delay and it is much more suitable for dynamic cognitive radio networks.

3. **Model Solution.** Sub-spectrum sensing model can be described as the formation of matrix calculation. The row represents the set of bands, while the column the user group. The matrix has only two elements 0 and 1. If $a_{i,j} = 1$, then $s_i{}'$ is assigned to G_j. Let $N = 6$, $k = 3$, the matrix satisfies the following condition:

1) Each row only has 3 elements of 1;
2) Each column only has 3 elements of 1;
3) Any three rows/columns are not the same.

With the model above, for $N = 6$, we can get part of the solution as shown with matrix $[a_{ij}]$:

$$[a_{ij}] = \begin{bmatrix} 451623 \\ 623514 \\ 135246 \end{bmatrix}, \begin{bmatrix} 451236 \\ 123564 \\ 562413 \end{bmatrix}, \begin{bmatrix} 563124 \\ 624513 \\ 136245 \end{bmatrix}, \begin{bmatrix} 436251 \\ 351462 \\ 523614 \end{bmatrix}, \begin{bmatrix} 546123 \\ 361452 \\ 412365 \end{bmatrix}$$

where a_{ij} is that the bands set $s'_{a_{ij}}$ has been assigned into group G_j.

We select the first three sets of solution to form 0/1 matrix $[b_{ij}]$ as follows:

$$\begin{bmatrix} 101010 \\ 010110 \\ 011001 \\ 100011 \\ 011100 \\ 100101 \end{bmatrix} \begin{bmatrix} 101010 \\ 011100 \\ 001011 \\ 100101 \\ 110100 \\ 010011 \end{bmatrix} \begin{bmatrix} 100110 \\ 010110 \\ 011001 \\ 001011 \\ 100101 \\ 111000 \end{bmatrix}$$

If $b_{ij} = 1$, $s_i{}'$ is assigned into G_j.

Take the distribution of the above three results into three clusters and do spectrum sensing, as shown in Figure 2 and Figure 3. We adopt the majority role to make final sensing decision. All cluster heads make their decisions according to the information received from the users within cluster, and communicate with the neighbor cluster heads to make the final sensing result. After this, the cluster heads broadcast the sensing result to all the cognitive users.

Channel allocation:

Each cluster head makes decision after processing sensing information from cognitive users, then negotiations with other cluster heads to obtain the available channel (free

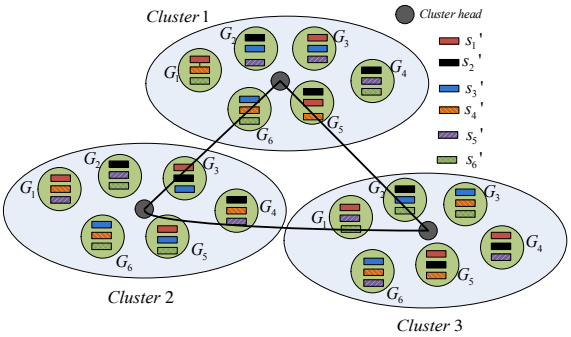

FIGURE 2. User group and band division in a cognitive network with three clusters

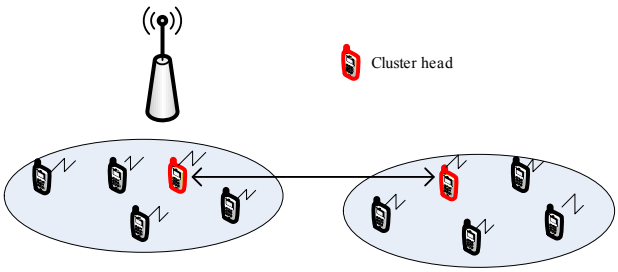

FIGURE 3. The model of sub-spectrum sensing scheme

spectrum) list of the cluster, and then broadcasts the list to the whole network. All cognitive users update their lists of available channels and apply for band according to the information. Taking into account the number of cognitive users, band applications conflicting is inevitable. We use reputation value to improve the enthusiasm of cognitive users to sense and make the sensing information much more reliable. For the users applying for the same band, the higher the reputation, the more opportunities the user gets. Besides reputation, we use sub-slot polling to ensure fairness. This scheme can prevent users with high reputation value from occupying band maliciously or make the allocated band in the idle state so that it cannot be used for other users.

4. **Model Analysis.** For our simulation, there are 13 cognitive users and one cluster head in a cluster. The users are $U_1, U_2, U_3, \ldots, U_{13}$, and 12 channels A, B, C, D, E, F, G, H, I, J, K, L. We choose $k = 12$, $N = 6$, $n = 13$ in the experiments. We represent the 12 channels with A, B, C, D, E, F, G, H, I, J, K, L, and bind two of them together in the sequence of the latter, and then put them into $s_1{}'$, $s_2{}'$, $s_3{}'$, $s_4{}'$, $s_5{}'$, $s_6{}'$ in turn according to the steps described in model of cluster, as shown in Figure 4 and Figure 5.

The results of the cooperative sensing of channels AB, EF, KL are: 1 1 1 1 1 0, while using the sub-spectrum sensing, the results are shown in Table 2.

TABLE 2. Sensing results with sub-spectrum sensing

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}
AB	00		00		11		11		00		00	
EF	01			01	11		11			01	01	
KL			10		11	11			10		10	10

The traditional cooperative sensing result is shown in Table 3. From the sensing result of channel AB, EF, KL, we compare the two schemes on system overhead and final

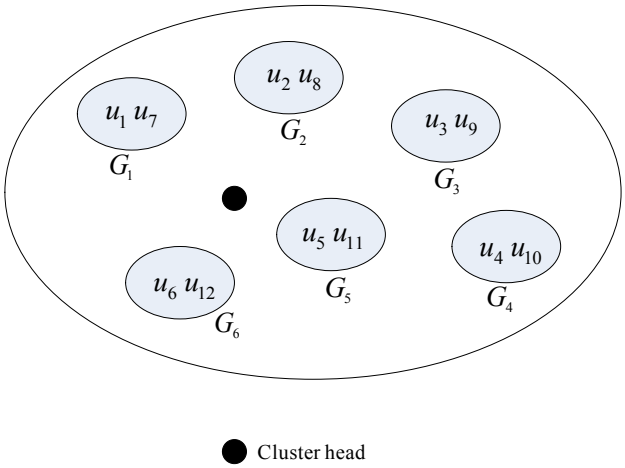

FIGURE 4. User group within a cluster (6 groups formed by 13 cognitive users)

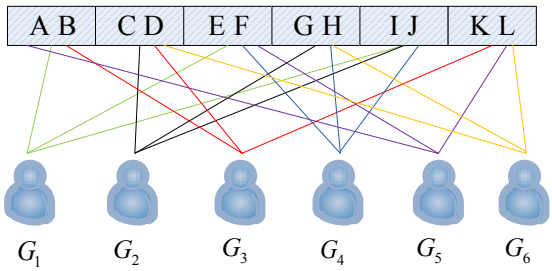

FIGURE 5. Sensing allocation in sub-spectrum sensing scheme within a cluster

TABLE 3. Sensing results with traditional cooperative sensing

	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}
A	0	1	0		1		1		1		0	
B	0	1	0		1		1		1		0	
C	1	1	0	1		1		1	0	1		1
D	1	1	1		1	1	1	1	1	1	0	0
E	0			0	1		1			0	0	0
F	1			1	0	1	0			1	1	
G	1	1	0	0		0	0	1	0	0	0	0
H												
I	1	1	1			1	1					0
J		1		1			0	1	1	0	0	1
K		1	1	1	1	0	1		0		1	0
L		1	0	0	1	1	1		0	1	0	1

decision respectively. As shown in Figure 6 and Figure 7, we can conclude that our scheme is less in system cost and can defense cheating partner effectively. From Table 3, we can see the channel H is non-sensing channel and this may cause incomplete final decision. As shown in the above results, U_5 and U_7 may be the attackers. Using the sub-spectrum sensing, we can obtain the sensing result of channel AB, EF, KL, which are 0 0 0 1 1 0. After analyzing the results of all the sensing channel, attackers can be found. The random spectrum allocation may result in the emergence of small probability

event, which means the falsification of some data could not be detected. This problem can be solved by the upper layer, and the cluster head will make the final decision according to the sensing results of other clusters. Besides, the scheme can defense Sybil attack with Identity-based validation techniques and dynamic updating. As it says, the scheme we proposed has the characteristic of multi-reliability.

The sub-spectrum sensing scheme applies in the condition that the number of the spectrum splits K is more than the number of the bound bands set N. The more the value of K/N, the better performance is the scheme. The users in the cognitive network must be equipped with multi-antenna due to the requirement of multi-band sensing in each group, in which the number of the spectrum splits should not be too much, which can be specified by changing the value N according to the network coverage.

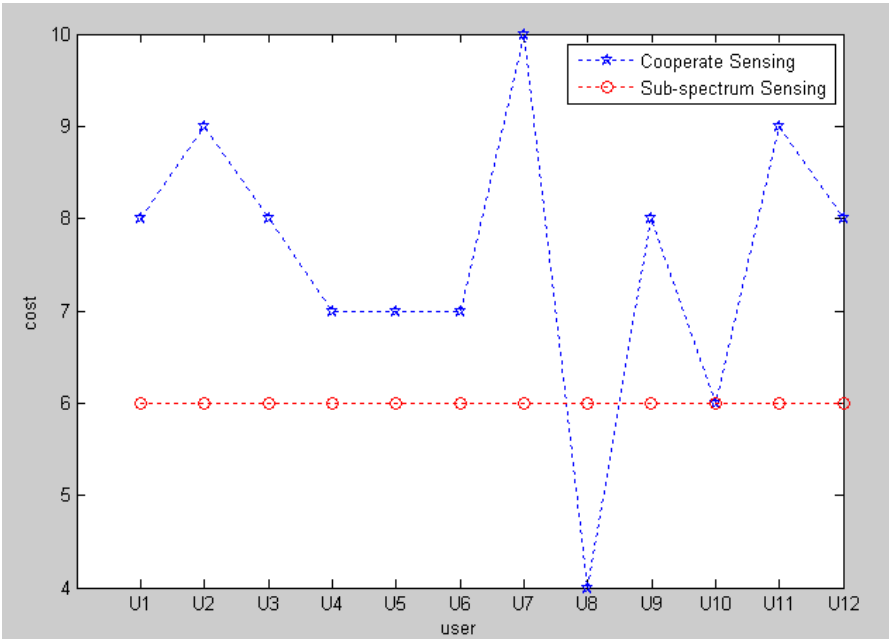

FIGURE 6. Sensing cost of users

The scheme we proposed can defense cheating partner by dividing users into different groups, band division and sub-spectrum sensing. The three stages use modular arithmetic, non-overlapping random distribution and multi-user sensing to prevent cheating partner attack, and greatly reduce the probability of SSDF attacks. In the case of unknown N, the probability of successful attacks will decrease quickly with the increasing of n/N. If attackers have obtained N, the probability of successful attacks will decrease with the increasing of n:

$$\frac{1}{(N-1)} \times \frac{1}{(N-2)} \times \frac{1}{\frac{n}{N}} \times \frac{1}{\frac{n}{N}} = \frac{N^2}{(N-1)(N-2)n^2} \tag{9}$$

With the attack probability under certain conditions, we can calculate dynamically changing value N from the model.

The reputation value of each user dynamic changes after each feedback, and this can update network state in real time. If there is a malicious user tampering sensing data, all neighbor nodes can detect it and its reputation value will be decreased. Once the reputation value is under some level, the user will be removed from the cluster.

In wireless environment, the signal transmission will be affected by shadow, multi-path and so on, and leak detection may occur as a result of interference to primary users.

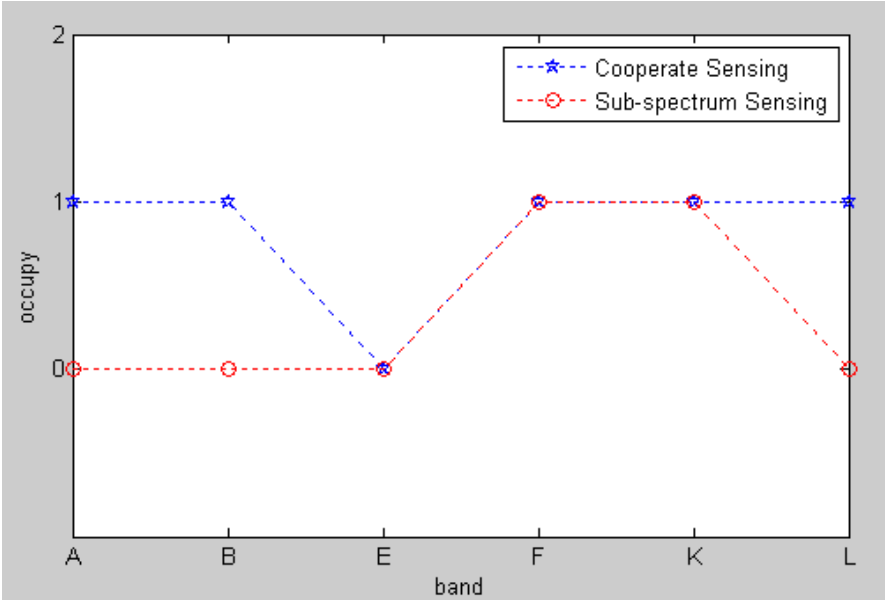

FIGURE 7. Final sensing results

Cooperative sensing technology makes decision of the free spectrum through integrated analysis using multi-node collaboration ships to improve the reliability and accuracy of the detection.

Cognitive users in each group only sense sub-region spectrum instead of all the bands with much less energy cost. Besides, each band split is present in k different partitions, so that even if a majority of a partition node is malicious, it cannot affect the final judgment.

For the different reputations of the different network nodes, the sensing data that each node uploads cannot be simply perceived as a factor in the final decision during data fusion process. In this scheme, the cluster head takes the reputation value as a reference to make the final decision, meanwhile, it makes more reliable judgments. If the user has been in a very low value after calculation in a long time, it can be considered as a malicious user and withdraw it from the network. However, for the user with high reputation value, it does not only play an important role in the final judgments, but also improves the user's permissions according to combine the reputation value and sub-slot polling. The sub-slot polling can avoid the phenomenon that users with higher reputation value do not use this frequency spectrum applied for a long time, so that each cognitive user has access right to use the idle frequency band. Meanwhile, it can not only enhance the positive sensing of users, but also take into account the fairness of the spectrum allocation.

For the dynamic characteristic in cognitive radio networks, the white holes of spectrum always change rapidly due to the emergence of primary users. To maximize spectrum efficiency without interfering primary users, cognitive users should reduce the sensing time delay and make sensing results as soon as possible. In distributed environment, users could exchange information with neighbor nodes and reach the final decision by diffusing the entire network. But the time delay is longer and it is not suitable for cognitive radio networks. In our scheme, we adopt clustering model in which cognitive users can only transmit their sensing data to the cluster head directly. After the negotiation of cluster heads all cognitive users can obtain the final sensing result. This communication model is more quickly than diffusing the entire network.

5. **Conclusions.** This paper proposes a sub-spectrum sensing scheme based on reputation in which cognitive users can sense part of bands instead of all bands, but this not only reduces costs, also ensures the reliability. Cluster head makes final decisions using reputation values to increase access priority of high-reputation-value users. The sub-spectrum sensing scheme not only decreases energy consumption, but also defenses SSDF attacks efficiently. Besides, it can motivate the enthusiasm of cognitive users to sense and make the sensing information much more reliable with consideration of reputation and balance fairness with the sub-slot method. Spectrum sensing is the previous work in cognitive radio networks; only obtaining the accurate white holes can we do the next stage and communicate with the idle spectrum bands. In our future work, we will test the spectrum sensing result by accessing the "white holes" the cluster heads broadcasted and update the reputation of cognitive users by matching the sensing result with the channel access.

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