Research on the scheme of radio cooperative spectrum sensing for offshore ships based on trust degree in Ad Hoc network mode

Jiaming Zhang, Baihai Zhang, Senchun Chai*, Lingguo Cui and Fenxi Yao
School of Automation, Beijing Institute of Technology, Beijing 100081, P.R. China
zjmtx97@163.com; chaisc97@bit.edu.cn*

Abstract. Radio communication is an important part of maritime communication. As the number of ships in the offshore area continues to increase, spectrum resources appear to be particularly tight. In this work, a trust-based cooperative spectrum sensing scheme in Ad Hoc network is proposed to improve the accuracy and reliability of maritime radio communications. This scheme first divides the ship nodes into different subnets according to the Ad Hoc network protocol. And after the malicious ship nodes are selected based on actual conditions, a trust-based collaborative spectrum sensing fusion method will be given, that is, a smaller trust weight is given to malicious nodes, the method will be more trustworthy to receive the spectrum occupancy information provided by ship nodes with a higher degree of trust. Simulations have been performed to illustrate the high detection probability of the proposed spectrum sensing scheme. Therefore, it is feasible and beneficial to apply the proposed spectrum sensing scheme to improve the trustworthiness of maritime radio communication.

1. Introduction
With the rapid development of wireless communication, the requirements for communication quality are now higher and higher. At the same time, with the substantial increase in the number of radio equipment, the use of spectrum resources is particularly important, which is more prominent in the field of offshore ship communications. The current maritime communication methods are mainly radio communication and satellite communication[1]. Compared with satellite communication, radio communication is much cheaper and has a higher transmission data rate. Therefore, it is commonly used in ship-to-shore communications and ship-to-ship communications in offshore environments.

The radio spectrum is a very precious natural resource, and its allocation is strictly managed by the radio regulation department. At present, many countries have formulated spectrum allocation plans in their region, which can simply avoid mutual interference between different frequency bands. However, some frequency bands are used very frequently during a certain period of time, while other frequency bands are not used by users, resulting in a waste of spectrum resources[2][5]. Cognitive radio[6] is generally considered to be a technology that efficiently utilizes the wireless spectrum, which uses spectrum sensing behavior to determine signal occupancy. At present, common spectrum sensing technologies include single node spectrum sensing and cooperative spectrum sensing. In realistic environments such as terminal concealment, signal attenuation, and multipath shadows, cooperative spectrum sensing has a better effect than single node spectrum sensing.

However, for areas with complex frequency spectrum such as offshore environment, the wireless environment may be poor or some ship nodes have their own equipment failures, which may send wrong
perception information and affect the final decision on whether the spectrum exists. Based on this phenomenon, this paper combines the environment of the Ad Hoc network to study the cooperative spectrum sensing technology of ship nodes based on the trust degree of the nodes, that is, to reduce the trust level of the malicious nodes in the network. Compared with traditional methods without trust, the method proposed in this paper can significantly improve the quality of spectrum perception in complex offshore environments.

2. System model

2.1. Model of cooperative spectrum sensing

The cooperative spectrum sensing model can be simply divided into three parts: the Primary User (PU), Sensor Nodes (SNs) and the Fusion Center (FC). The PU is employed to generate and transmit spectrum signals, the SNs are used to sense spectrum in the environment cooperatively, FC could collect the signals from SNs, operate fusion algorithm and make the final decision. The realization of the cooperative spectrum sensing method is inseparable from the single node spectrum sensing. At present, there are different methods which have been proposed for single node spectrum sensing, such as matched filter detection [7], cyclostationary feature detection [8] and energy detection [9]. Since the energy detection method is easy to operate and cost less resources, the cooperative spectrum sensing method proposed in this paper will be based on this method.

\[
R(k) = \begin{cases} 
H_0: n(k) \\
H_1: g S_{pu} + n(k) 
\end{cases}
\]  

Figure 1. Simplified model of cooperative spectrum sensing.

The brief signal flow diagram of the cooperative spectrum sensing method is shown in figure 1. If a binary hypothesis problem is used to represent the detection of the SNs, \( H_0 \) indicates that SNs cannot detect the existence of PU, while \( H_1 \) means that SNs can detect the existence of PU. The mathematical expression can be obtained as shown in equation (1).

In the model of cooperative spectrum sensing in this paper, it is assumed that each SN is independent of each other. In the above equation, \( k \) means the \( k \)-th signal channel, \( n \) is assumed to be the additive Gaussian noise add on each SN, \( g \) represents the channel gain of each SN, and \( S_{pu} \) is considered as the spectrum signal generated by PU.

After a single node completes spectrum sensing, there are the other two important stages in the collaborative spectrum sensing method, as shown in figure 1, namely energy detection and soft combination & adjudication. These two stages are explained separately below.
Energy detection: During spectrum sensing, each SN will sample $M$ times in a period of time to perform energy detection. $R_i$ represents the received signal of SN the $k$-th signal channel, $E(k)$ means the final result after energy detection. The mathematical expression can be as shown in equation (2).

$$E(k) = \frac{1}{M} \sum_{i=1}^{N} R_i(k)^2$$ (2)

Soft combination & adjudication: After energy detection, each SN will report its detection result to FC, soft combination will be applied at the FC to calculate the final cooperative results. Based on the results obtained, the FC will give the final decision whether PU uses the frequency band. Regarding soft combination & adjudication, fusion Criteria is the key to ensuring the accuracy of its results. In the next section, it will be discussed in detail.

2.2. Mathematical model of fusion criteria

The accuracy of spectrum sensing can be described as detection probability ($P_d$). In the case of the same signal-to-noise ratio (SNR) and false alarm probability ($P_f$), it is generally believed that the higher the value of $P_d$, the better the accuracy of the result. This paper use ROC diagram to evaluate the scheme performance, where the curve of $P_d$ is plotted versus $P_f$. Therefore, the quality of the strategies proposed in this paper can be compared by observing the ROC curve.

The general form of decision fusion criterion is $K/N$ criterion$^{[10]-[12]}$. This criterion means that if there are $K$ or more users among $N$ users who determine that the primary user exists, then the final decision is that the primary user exists, otherwise it is deemed that the primary user does not exist. In the cooperative network, the false alarm probability and detection probability of the $i$-th sensor node are $P_{f_i}$ and $P_{d_i}$, respectively, and the local decision is recorded as $u_i$. When the main user exists, $u_i = 1$; otherwise, $u_i = 0$. As shown in the following equation (3).

$$u_i = \begin{cases} 0, & H_0 \\ 1, & H_1 \end{cases}$$ (3)

In this case, the probability of cooperative false alarm and cooperative detection probability are respectively shown as equation (4) and equation (5).

$$Q_f = \sum_{j=K}^{N} \sum_{\sum u_i = j} \prod_{i=1}^{N} (P_{f_i})^{u_i} (1-P_{f_i})^{1-u_i}$$ (4)

$$Q_d = \sum_{j=K}^{N} \sum_{\sum u_i = j} \prod_{i=1}^{N} (P_{d_i})^{u_i} (1-P_{d_i})^{1-u_i} = 1-Q_f$$ (5)

The following introduces several common forms of $K/N$ criteria$^{[13]}$.

2.2.1. Or Criterion. The paragraph text follows on from the subsubsection heading but should not be in italic. In the $K/N$ criterion, let $K = 1$. This scheme sacrifices the false alarm probability in exchange for a small missed detection probability. The cooperative false alarm probability and the cooperative detection probability are respectively shown as equation (6) and equation (7).

$$Q_{f,or} = 1-(1-P_f)^N$$ (6)

$$Q_{d,or} = 1-(1-P_d)^N$$ (7)

2.2.2. And Criterion. In the $K/N$ criterion, let $K = N$. This scheme can obtain a low false alarm probability, but the probability of missed detection is relatively high. Its cooperative false alarm
probability and cooperative detection probability are respectively shown as equation (8) and equation (9).

\[ Q_{f_{\text{and}}} = P_f^N \]  
\[ Q_{d_{\text{and}}} = P_d^N \]  

2.2.3. **Majority Criterion.** The paragraph text follows on from the subsubsection heading but should not be in italic. In the \( K/N \) criterion, \( K = \left\lceil \frac{(N + 1)}{2} \right\rceil \). The cooperative false alarm probability and the cooperative detection probability are respectively shown as equation (10) and equation (11).

\[ Q_{f_{\text{majority}}} = \sum_{i=0}^{N} \binom{N}{i} P_f^i \left(1 - P_f\right)^{N-i} \]  
\[ Q_{d_{\text{majority}}} = \sum_{i=0}^{N} \binom{N}{i} P_d^i \left(1 - P_d\right)^{N-i} \]

3. **Ship Ad Hoc network in the offshore**

In the offshore environment, a large number of ships move freely, and its network topology change frequently, so it is difficult to find a stable center for information processing. This paper organizes this network structure through the Ad Hoc network. After the ship network is established, the cluster head ship can be selected as the \( FC \) and the base station can be selected as \( PU \) for subsequent analysis according to the classification organization.

3.1. **Model of ship Ad Hoc**

In the ship networking method mentioned in this article, the ship is divided into different networks based on the position coordinates provided by the navigation and positioning system. That is, the structure of the cluster in the Ad Hoc network\(^{[14][15]}\). The number of ships can be adjusted according to the diameter of the network. The model of ship Ad Hoc network is shown as figure 2.

3.2. **Cooperative spectrum sensing in ship networking**

In the ship networking strategy proposed in this article, all ships will perform energy detection at a certain frequency in the standby state. Once the channel is occupied due to too many ship nodes, the first ship node that detects the abnormal signal will be temporarily used for \( FC \). \( FC \) will send alarm signals to other ship nodes in its own network. After receiving the alarm signals, these ship nodes will...
automatically work according to the role of SNs and send the spectrum detection after energy detection to FC.

After that, the ship node which works as FC working mode will receive the signal from each ship node in the network and give the result of whether the frequency band exists according to the soft combination & adjudication algorithm. Finally, the result will be notified back to the ships in the network.

Figure 3 is the topological diagram of cooperative spectrum sensing in ad hoc network of ships, where PU uses shore-based base station for illustration.

4. Cooperative spectrum sensing based on trust degree

The cooperative spectrum sensing based on trust degree described in this section belongs to the algorithm embedded in soft combination & adjudication. It characterizes the decision to adopt the weight of its spectrum sensing results based on the trust degree of the node in the network. Because in the intricate offshore environment, there will be some ship nodes that are far away from the PU node which will cause the spectrum results to be distorted, or the node never monitor or send spectrum sensing information, which are called malicious node ship [16]-[18]. After determining that it is a malicious node through location acquisition and other methods, the scheme proposed in this paper gives it a smaller weight so that it has the lowest impact on the final fusion.

4.1. Spectrum sensing request

Assuming that there are \( n \) ship nodes in the ship network that issue spectrum sensing requests, it can be determined that \( n \) is less than the total number of nodes in the ship network \( N \) and greater than 0.

4.2. Spectrum detection

After the base station PU determines the occupancy status of the spectrum, it is assumed that \( m \) nodes in the ship networking environment have detected the frequency band, where \( m \) is a value greater than 0 and not greater than \( N \).

4.3. Behavior matrix update

Taking the effects of multipath and shadow effects into account, this paper assumes that even malicious nodes will have a 15% correct perception probability due to these factors; and normal users will have a 15% false perception probability due to the existence of these factors. In this case, use the following to update the behavior matrix:

\[
\text{Algorithm: the update of behavior matrix}
\]

Step 1: the update of \( M_{\text{sen}} \)
// $M_{\text{sn}}$ means perceived behavior matrix, the row index indicates the ID of the PU, and the column
// index indicates the ID of the SN
if $m(i)$ belongs to malicious users// $m$ means the nodes detect the signal
  if rand>85%
    $M_{\text{sn}}(p,d) = V(p)$ // $V(p)$ means the status of PU $p$
  else
    $M_{\text{sn}}(p,d) = 1 - V(p)$
  end
else
  if rand>15%
    $M_{\text{sn}}(p,d) = V(p)$
  else
    $M_{\text{sn}}(p,d) = 1 - V(p)$
  end
end

Step 2: the update of $M_{\text{resp}}$ & $M_{\text{resp\_real}}$
// $M_{\text{resp}}$ means perceive response matrix, one row and n columns, each column corresponds to the
// number of perceive responses for n nodes
// $M_{\text{resp\_real}}$ means the real perceive response matrix, the matrix size is equal to $M_{\text{resp}}$
$M_{\text{resp}}(d) \leftarrow M_{\text{resp}}(d) + 1$
if $M_{\text{sn}}(p,d) = V(p)$
  $M_{\text{resp\_real}}(d) \leftarrow M_{\text{resp\_real}}(d) + 1$
end

4.4. Trust degree calculation
When the number of response times of a node is zero, the node is considered to be faulty and a trust of
zero weight is given; the trust degree of other nodes is attached with the weight value based on the ratio
of the real corresponding times to the number of perceived responses to realize the calculation of the
trust degree. The nodes that need to be trusted by the method proposed in this paper need to satisfy the
following equation, among them, $D_{\text{trust}}$ is the trust degree given to node $i$ by the method proposed in
this paper, and $\lambda$ is the trust degree threshold, which can filter out the perception results of malicious
users based on the trust degree threshold.

$$D_{\text{trust}} = \frac{M_{\text{resp\_real}}}{M_{\text{resp}}} \geq \lambda$$ (12)

5. Experiment Results
This section compares and analyzes the scheme mentioned in this article and the method without trust
through the ROC diagram. This paper uses MATLAB to simulate. First, assume that the judgment results
between the nodes are independent of each other, the channel parameters and fading effects are also
independent of each other, and the malicious node only sends data that is opposite to the judgment result.
Then, the channel and Ad Hoc network configuration parameters are as follows:

| Table 1. The channel and Ad Hoc network configuration parameters. |
|---------------------------------------------------------------|
| the channel configuration parameters                        |
| SNR | signal bandwidth $w$ | sampling frequency | signal phase |

In this paper, a Monte Carlo experiment is carried out, and the number of experiments is set to 200 times. Figure 4 shows the general algorithm under the $K/N$ criterion, figure 5 to figure 7 are several common forms of $K/N$ criteria mentioned above.

From figure 4 to figure 7, it can be indicated that in each figure, the cooperative spectrum sensing scheme mentioned in this paper is closer to the upper left corner than the method without trust under normal circumstances, that is, the area enclosed by the horizontal axis is larger. It proves that the scheme mentioned in this article has better performance in the same environment than the method without trust.

6. Conclusion
The scheme of radio cooperative spectrum sensing for offshore ships based on trust degree in Ad Hoc network mode has been presented in this paper. And it aims to solve the problem of ships' cooperative

| K/N criterion | “K rank” Fusion Collaboration Method |
|---------------|-------------------------------------|
| $P_D$         |                                     |
| $P_F$         |                                     |
| Detection probability | 0.9                              |
| False alarm probability | 0.1                              |

| “And” Fusion Collaboration Method |
|-----------------------------------|
| $P_D$                             |
| $P_F$                             |
| Detection probability | 0.9                              |
| False alarm probability | 0.1                              |

| “Or” Fusion Collaboration Method |
|----------------------------------|
| $P_D$                            |
| $P_F$                            |
| Detection probability | 0.95                            |
| False alarm probability | 0.05                             |

| “Majority” Fusion Collaboration Method |
|----------------------------------------|
| $P_D$                                  |
| $P_F$                                  |
| Detection probability | 0.9                              |
| False alarm probability | 0.1                              |
perception of spectrum in the offshore environment, especially for situations that affect ship data transmission in areas with complex environments. Compared with the algorithms without trust, this solution has better performance under the K/N criterion and its three common forms.

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