Self-weighted Decentralized Cooperative Spectrum Sensing Based On Notification for Hidden Primary User Detection in SANET-CR Network

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Abstract

The ship ad-hoc network (SANET) extends the coverage of the high data-rate terrestrial communications to the ships with the reduced cost in maritime communications. Cognitive radio (CR) has the ability of sensing the radio environment and dynamically reconfiguring the operating parameters, which can make SANET utilize the spectrum efficiently. However, due to the dynamic topology nature and no central entity for data fusion in SANET, the interference brought into the primary network caused by the hidden primary user requires to be carefully managed by a sort of decentralized cooperative spectrum sensing schemes. In this paper, we propose a self-weighted decentralized cooperative spectrum sensing (SWDCSS) scheme to solve such a problem. The analytical and simulation results show that the proposed SWDCSS scheme is reliable to detect the primary user in SANET. As a result, secondary network can efficiently utilize the spectrum band of primary network with little interference to primary network. Referring the complementary receiver operating characteristic (ROC) curves, we observe that with a given false alarm probability, our proposed algorithm reduces the missing probability by *27%* than the traditional embedded spectrally agile radio protocol for evacuation (ESCAPE) algorithm in the best condition.

Keywords: SANET, cognitive radio, hidden primary network, decentralized cooperative spectrum sensing, self-weighted sensing

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1. Introduction

The existing communication systems over sea, such as automatic identification system (AIS) [1], only provide low data-rate non real-time services such as ship identification, positioning, and email, etc. Satellite system is able to cope with such service requirements, but the cost will be high. For the purpose of enhancing the service quality of maritime communications, radio transmission technologies (RTT) for ship ad-hoc network (SANET), based on the Recommendation ITU-R 1842-1 (VHF band) [2], are designed in our former study [3]. Moreover, in this paper, to solve the tradeoff between the congested spectrum band and the growing demands of high data-rate, real-time services (e.g., multi-media services and video surveillance), we employ the cognitive radio (CR) technique to support SANET opportunistically access other primary network's spectrum band.

CR technique is considered as a potential solution to solve spectrum inefficiency problem. It is an intelligent wireless communication system that can change its transmitter parameters based on the interaction with its surrounding environment. By exploiting under-utilized or un-utilized spectrum band opportunistically, it provides a large amount of new spectrum availablities. There are two main entities in CR systems, namely primary user (PU) and secondary user (SU). PU has the license to operate in a certain spectrum band, while SU is permitted to transmitt or receive signal on this spectrum band only when PU is inactive to avoid interference to PU. Therefore, the basic idea of CR network is that the SU needs to vacate the band once the PU is detected [4]. Consequently, spectrum sensing, the process of detecting PU by sensing the surrounding radio environment, is the key technique to ensure SUs would not interfere to PUs. However, hidden primary user problem may decrease the spectrum sensing accurracy of a SU. Therefore, a cooperative spectrum sensing scheme is required to reliably solve the hidden primary user problem, providing a precise sensing result. In this paper, we implement the CR technique to the SANET, and propose a decentralized cooperative spectrum sensing algorithm for the SANET-CR system to avoid hidden primary user problem.

The rest of this paper is orgnized as follows. In section 2, we propose a SANET-CR system, and introduce the hidden primary user problem in the system. Section 3 reviews the local spectrum sensing methods under Rician fading environment and some traditional cooperative spectrum sensing schemes. Our proposed self-weighted decentralized cooperative spectrum sensing (SWDCSS) algorithm is presented in section 4. The simulation results and analyses are shown in section 5, and finally, we conclude this paper in section 6.

2. Proposed SANET-CR System

In our former work [5], we proposed three senarios for maritime wireless communications which is applied to the locations of harbor, shore, and ocean, respectively. Based on these senarios, in this paper we propose a SANET-CR system, where the CR technology is introduced into the SANET system, to make SANET users be able to opportunistically access the licensed spectrum band of other networks. In this way, the tradeoff between the congested spectrum band and the growing demands of high data-rate and real-time services can be managed. **Fig. 1** depicts the architecture of the SANET-CR system, which describes SANET

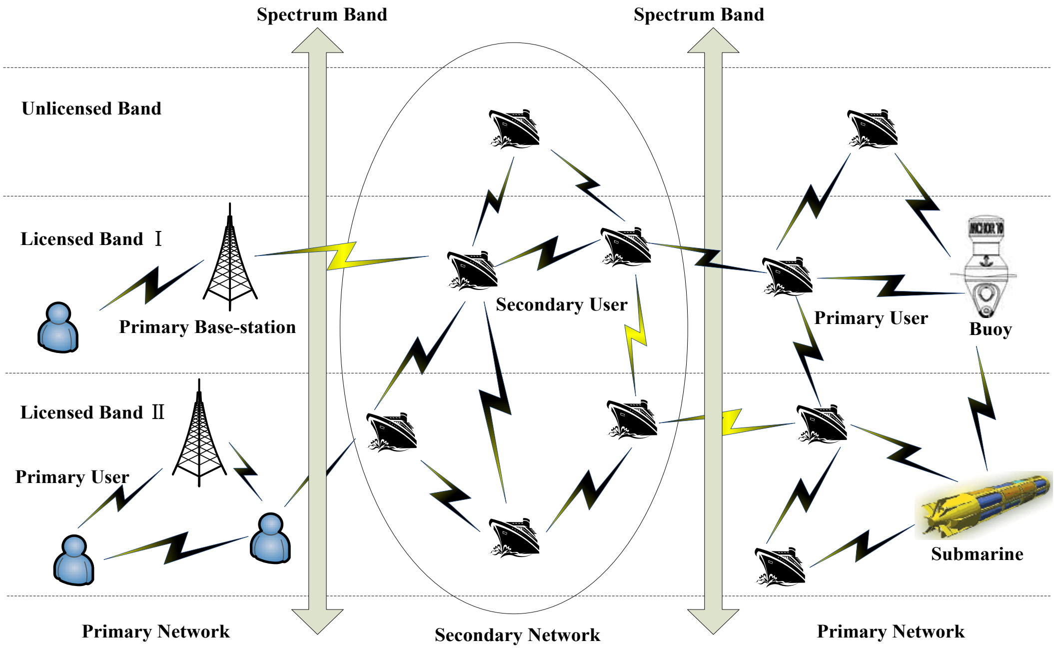

Fig. 1. The architecture of SANET-CR system.

as the secondary network (SN). Around harbor or shore, we consider the terrestrial cellular network as primary network (PN). In the ocean enviroment, other maritime ad-hoc networks could be identified as primary networks. When SANET is closer to seashore, it accesses the unused spectrum band of the terrestrial cellular network for its own communications. Similarly, when SANET is in the ocean, it can use the licensed band of other maritime ad-hoc network opportuniscally. Notice that the SUs in SANET should not interfere the PU when they occupy the spectrum band of PN. Therefore, SUs should discover available spectrum holes over a wide frequency range for their transmission, and keep surveilling the spectrum band during the transmission. Once the presence of PUs is detected, SUs should evacuate the spectrum band so as to avoid inteference to PN.

However, due to the hidden primary user problem caused mainly by the position of SUs in maritime environment, the SUs may not detect the existence of PUs, then it inevitably introduces the interference into PNs. As an example illustrated in Fig. 2, the left and right dot circles represent the operating ranges of the base-station (BS) in primary network and SU-A in secondary network, respectively. When PU-A is under the sleep mode, SU-A can occupy the spectrum band of PU-A to communicate with other SUs. Once BS sends the wakeup signal to PU-A, SU-A cannot detect the signal from BS to PU-A since SU-A is out of the operating ranges of BS. SU-A, however, continues to transmit signal over the spectrum band of PU-A, causing unwanted interference to PU-A. To solve such a hidden node problem, the cooperative spectrum sensing, where several SUs, e.g., including SU-B in Fig. 2, collaborate to detect the PU, is used to reduce the missing probability of detecting the PU. Due to the dynamic topology nature and no central entity for data fusion of SANET, in this paper, we propose a self-weighted decentralized cooperative spectrum sensing (SWDCSS) algorithm based on the SU notifications to reliably solve the hidden primary user problem for SANET.

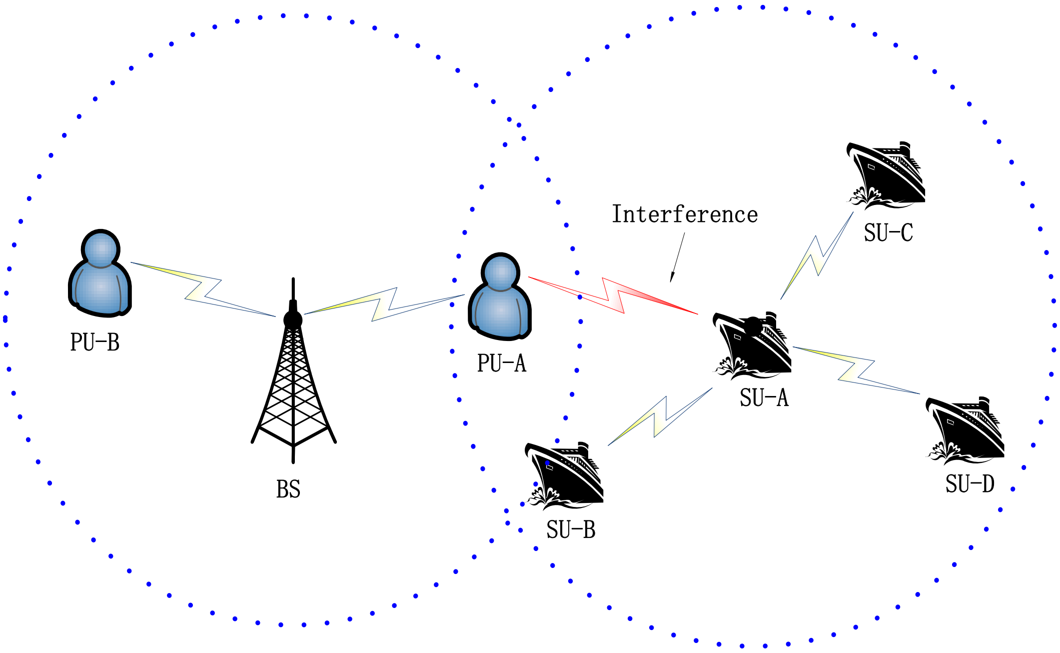

Fig. 2. Hidden primary user problem in SANET-CR system.

3. Spectrum Sensing under Flat Fading Channel

3.1 Selection of the Local Spectrum Sensing Methods

Before performing cooperative spectrum sensing, every SU should detect whether an active PU is existing in its local sensing area. There are three widely used spectrum sensing methods: matched filter detection, energy detection, and cyclostationary feature detection [6, 7].

Under the consideration of that the noise in maritime environment is relatively steady and the low computational complexity of the energy detection method is required, we consider the energy detection as our local spectrum sensing method.

3.2 Performance of Energy Detection under Flat Fading Channel

The classic energy detection method is based on the following hypothesis model [4]:

$$y(t)=\begin{cases} n(t) & H_0\ , \\ hx(t)+n(t) & H_1\ , \end{cases} \tag{1}$$

where $y(t)$ is the signal received by the SU, $x(t)$ is the transmitted signal of the PU, h represents the gain of the channel, and $n(t)$ denotes a zero-mean additive Gaussian noise (AWGN). H_0 states that there is no PU signal in the detected spectrum band, while H_1 indicates that PU signal exists.

Define the detection probability (P_d) and false alarm probability (P_f) as:

$$P_d = P_r(Y > \lambda | H_1), \tag{2}$$

$$P_f = P_r(Y > \lambda | H_0), \tag{3}$$

where Y is the signal power received by the SU, λ is the threshold to determine whether the PU signal exists or not. Then the missing probability (P_m) can be expressed as:

$$\begin{aligned} P_m &= P_r(Y < \lambda | H_1) \\ &= 1 - P_d \, . \end{aligned} \tag{4}$$

The expressions of both P_d and P_f under AWGN channel can be obtained as in [8]:

$$P_d = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}), \tag{5}$$

$$P_f = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)}, \tag{6}$$

where $Q_u(.,.)$ is the generalized Marcum Q-function, $\Gamma(.)$ & $\Gamma(.,.)$ are the complete and incomplete gamma functions, respectively. u denotes the time bandwidth product and γ represents the SNR.

Considering that P_f is independent on SNR since it is defined for the case of no signal transmission, the expression of P_f under any fading channel remains the same. In this paper, we focus on P_d and P_m only. Equation (5) gives P_d under non-fading environment based on the instantaneous received SNR, where h is deterministic. When h varies due to fading, corresponding P_d must be calculated by

$$P_d = \int_x Q_u(\sqrt{2\gamma}, \sqrt{\lambda}) f_\gamma(x) dx, \tag{7}$$

where $f_\gamma(x)$ is the probability distribution function (pdf) of SNR under fading [9]. According to [10], the measured SANET flat fading channel follows the Rician distribution with the K-factor of 15 dB. When the signal experiences Rician fading, the pdf of γ will be

$$f(\gamma) = \frac{K+1}{\bar{\gamma}} \exp(-K - \frac{(K+1)\gamma}{\bar{\gamma}}) I_0(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}}}), \quad \gamma \geq 0, \tag{8}$$

where K indicates the Rician K-factor, $\bar{\gamma}$ denotes the average SNR, and $I_v(.)$ is the v-th-order modified Bessel function of the first kind. Then the corresponding P_d in (9) in the case of the Rician channel is obtained by averaging (5) over (8) as in [8]

$$P_{d\,Ric|u=1} = Q(\sqrt{\frac{2K\bar{\gamma}}{K+1+\bar{\gamma}}}, \sqrt{\frac{\lambda(K+1)}{K+1+\bar{\gamma}}}). \tag{9}$$

3.3 Traditional Cooperative Spectrum Sensing Schemes

As illustrated in section 2, a cooperative spectrum sensing scheme is required to solve the hidden primary user problem in SANET-CR system. The main idea of the cooperative sensing techniques is that each SU can individually sense the channel and exchange their local sensing results to decide if the medium is available [11]. As the example in **Fig. 2**, SU-A is far from BS, resulting missing detection of signal from BS to PU-A. However, SU-B is much closer to BS which has high opportunity to detect the signal of the primary network. By the support of SU-B, SU-A can vacate the spectrum band of PU-A so as to avoid interference.

Various kinds of cooperative spectrum sensing algorithms have been proposed in [12]-[17]. Generally, the cooperative spectrum sensing algorithms can be classified into two categories [11]. The first one is the centralized cooperative spectrum sensing (CCSS), in which a central entity gathers information from all the SUs to make a decision on the medium status. Then the central entity transmits its decision back to the receivers. The second one is the decentralized cooperative spectrum sensing (DCSS), in which the SUs share their sensing information and make their own decisions. For the CCSS, such as in [12], SUs send their local sensing results to a data fusion unit, which combines and processes all the sensing results. Then the data fusion unit transmits its decision back to SUs. However, CCSS is not suitable for SANET, since that SANET has a dynamic topology and usually there is no central entity available for data fusion in maritime communication systems. In [13], a DCSS based on SU notification protocol, namely embedded spectrally agile radio protocol for evacuation (ESCAPE), is proposed to disseminate the evacuation information among the local SUs. Even though some SUs cannot detect the presence of PU due to the hidden primary user problem, they can vacate the spectrum band efficiently when they receive the notification signal from other SUs. However, the ESCAPE is vulnerable to the inaccuracy of sensing results.

4. Proposed Decentralized Cooperative Spectrum Sensing Algorithm

4.1 Proposed SWDCSS Algorithm

In this section, we propose a self-weighted decentralized cooperative spectrum sensing (SWDCSS) algorithm to effectively reduce the missing probability. The proposed algorithm is a kind of the DCSS algorithms, which matches with the dynamic SANET environment (without the unit of central data fusion). In addition, a weighting factor $W_r(n)$ is introduced into our algorithm to further reduce the missing probability of the SANET-CR system, where n denotes the index of the sensing process and r indicates the r-th SU. The weighting factor is generated based on the historical sensing data, and the details of the proposed SWDCSS algorithm is illustrated in **Fig. 3**. There are total 7 phases in the proposed SWDCSS algorithm as follows.

Phase 1] Initialization

As the spectrum sensing process is started, the weighting factor is initialized to one, i.e., $W_r(1) = 1$ for all the SUs.

Phase 2] Local sensing

After initialization, every SU performs local sensing, i.e., energy detection to detect the activity of PU in their own operating range.

Phase 3] Weighting

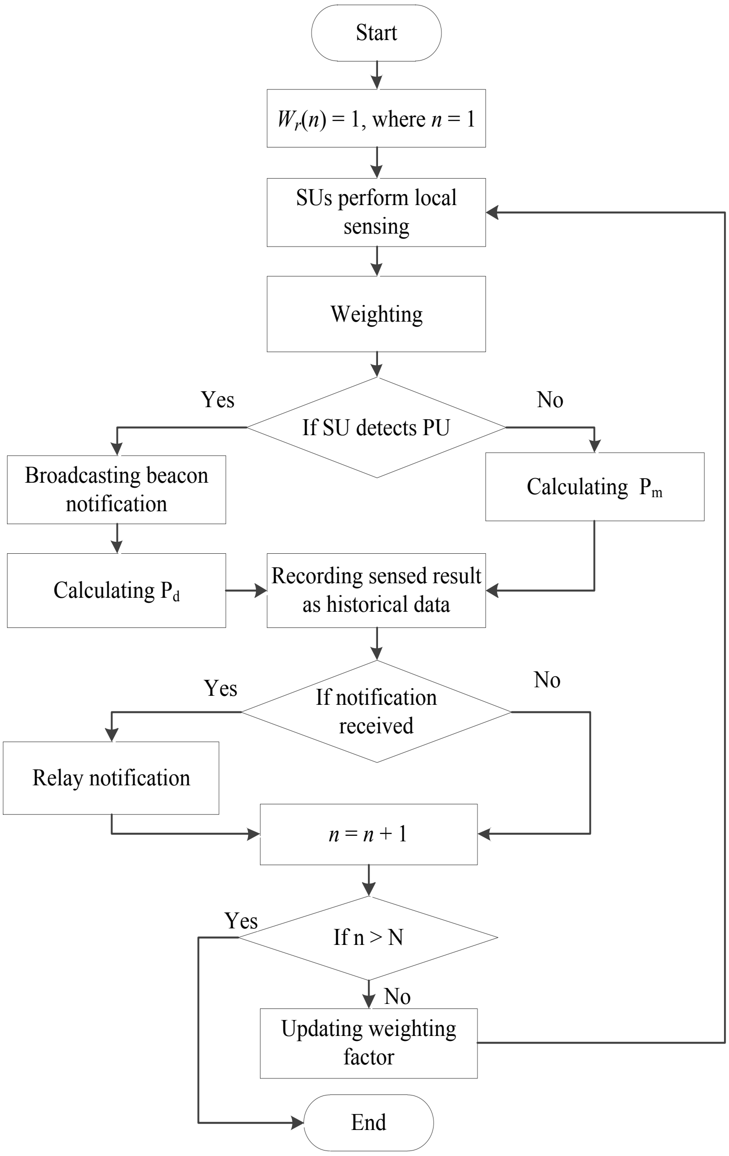

Fig. 3. Flow chart of the proposed SWDCSS algorithm.

When each SU gets its local sensing result, it should multiply the weighting factor to its local sensing result and feed the weighted sensing result to the next phase.

Phase 4] Notification

After weighting process, SUs have their weighted sensing results on the existence of an active PU in their operating range. Then SUs compare their weighted sensing results with a predefined threshold. Only the SU, whose weighted sensing result is bigger than the threshold, will broadcast its notification beacon to the local neighbor SUs. Otherwise, no action required.

Phase 5] Historical sensing data recording

In this phase, SUs calculate their detection probability if they detect the activity of any PU, otherwise they calculate the missing probability. Then they record the probability as historical sensing data for weighting factor update in phase 7.

Phase 6] Relay notification

When a SU receives a notification beacon from its neighbor, it relays this notification to its neighbor SU immediately. The purpose of relay is to make sure that the detection of PU activity can be shared among all the members within SN. Note that, a perfect relaying without collisions is assumed in this phase.

Phase 7] Weighting factor updating

At last, every SU should update their weighting factor for the next local sensing process. The principle of updating the weighting factor $W_r(n)$ is:

$$W_r(n)=\frac{P_{d\_r}(n-1)}{\overline{P_{d\_r}}}, \tag{10}$$

where P_d for the r-th SU is

$$\overline{P_{d\_r}}=\frac{\sum_{i=1}^{n-1}P_{d\_r}(i)}{n-1}. \tag{11}$$

If n does not exceed the maximal index N denotes the number of sensing process, system goes to phase-2. Otherwise, the spectrum sensing process is ended.

4.2 Analysis on the Proposed SWDCSS Algorithm

In (10), the weighting factor $W_r(n)$ is defined as the ratio of the detection probability of the last sensing process and the average value of all the historical detection probabilities. A bigger $W_r(n)$ means that the SU has higher probability of detecting PU. The received SNR is affected by the node location and the fading environment [18], and generally the correctness of SU's sensing results is increased with a higher received SNR. Therefore, in SANET-CR system, the location of SU is the most important factor that influences the correctness of the sensing results. The historical sensing data can reflect the change of a SU position. By this consideration, we use historical sensing data to calculate the weighting factor to weight every SU's local sensing result.

In our algorithm, if any SU detects the signal of the PU, it then notifies other SUs to vacate the PU's spectrum band. Assuming there are R SUs in the SANET, the detection probability Q_d and the missing probability Q_m of the SANET-CR system can be expressed as:

$$Q_d(n)=1-\prod_{r=1}^{R}W_r(n)[1-P_{d\_r}(n)], \tag{12}$$

$$\begin{aligned} Q_m(n) &= 1 - Q_d(n) \\ &= \prod_{r=1}^{R} W_r(n)[1 - P_{d\_r}(n)]. \end{aligned} \tag{13}$$

Consider that there are tens of SUs in local area, and they perform local spectrum sensing independently. In this case, the collisions may occur if the multiple notification beacons are transmitted at the same time. The slotted ALOHA algorithm is used in our algorithm to cope with the collisions [19]. Assume that there are R SUs, s beacons in one packet, and l SUs attempt to send notification beacon at the same instance, which becomes occupancy number of one beacon. The expected value $a_l^{s,R}$ of the number of beacons with occupancy number l is given as:

$$a_l^{s,R} = s\binom{R}{l}(\frac{1}{s})^l(1-\frac{1}{s})^{R-l}. \tag{14}$$

When the occupancy number $l = 1$, the notification beacon is successfully broadcasted without collision. Thus we have

$$\begin{aligned} A &= a_1^{s,R} \\ &= R(1-\frac{1}{s})^{R-1}. \end{aligned} \tag{15}$$

As a result, the missing probability in (13) becomes

$$\begin{aligned} Q_m(n) &= 1 - Q_d(n) \\ &= \prod_{r=1}^{A} W_r(n)[1 - P_{d\,r}(n)]. \end{aligned} \tag{16}$$

To the best knowledge of the authors, most of decentralized cooperative spectrum sensing algorithms are not proposed based on the historical sensing accuracy [15, 16]. The adoption of weighting the local sensing result makes the Q_m in (13) and (16) decreased further compared to the ESCAPE algorithm. Moreover, applying slotted ALOHA algorithm makes Q_m in (16) closer to the practical detection performance than that in (13).

Table 1. Simulation parameters

Parameters	Values
Carrier frequency	2.075 *GHz*
Bandwidth	50 *KHz*
SNR	5 *dB*
K factor	15 *dB*
Total Nr. of SUs	30

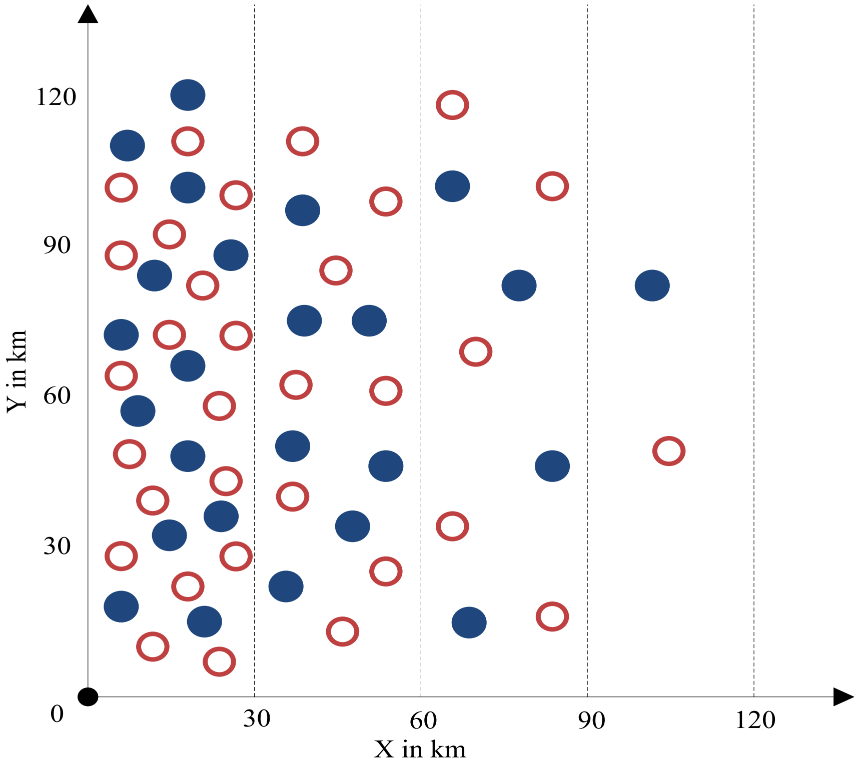

Fig. 4. Simulation scenario of the SANET-CR system. PUs by filled-in circles and SUs by hollow circles.

5. Simulation and Discussion

5.1 Simulation Scenario and Parameters

As shown in **Fig. 4**, we consider a scenario of 120 *km* by 120 *km* area with 4 hops in the area i.e., 30 *km* per hop. X-axes represents the distance from the seashore to the ocean, and Y-axes represents the distance along the seashore. The filled-in circles represent the ships which are communicating via PN, and the hollow circles represent the ships which are communicating as SUs. The first 30 *km* along the X-axes is the near-shore area where the density of ships is the highest. As the distance increases in X-axes, the density of ships decreases. This assumption is

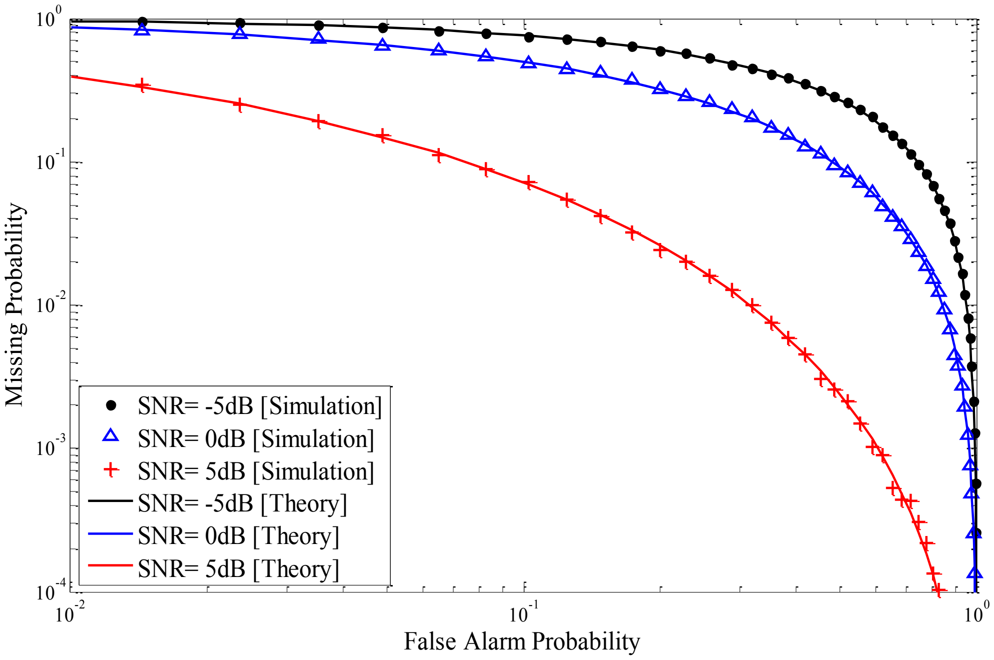

Fig. 5. Complementary ROC curves of the proposed SWDCSS with different SNR under Rician channel with $K = 15$ *dB*.

based on the fact that the number of ships are more in the near-shore area, while less in the ocean. In this paper, we consider all the ships (PUs and SUs) are deployed with the same distributation.

Within the region of the first hop (first 30 *km*), the PN becomes terrestrial cellular network, whose carrier frequency is 2.075 *GHz* in this paper. In the next 3 hops (far away from seashore), the PN networks can be other types of networks such as AIS and satellite communication systems, and the carrier frequency and the licensed frequency band can be totally different from those in the first hop. Since that there are more ships located in the first hop and so the probabiltity of introducing interference by the hidden primary user is higher, we take the network scenario in the first hop area (first 30 *km*) as an example to evaluate the performance of the proposed SWDCSS algorithm. In the first hop area, assume that the number of ships (i.e., SUs) adopted in the simulation is 30. The SANET system bandwidth is set to 50 *KHz* according to Recommendation ITU-R 1842-1 [2], and the Rician K factor is set to 15 *dB* as described in section 3. In the simulation, we predefine a set of false alarm probability P_f as $0 < P_f < 1$, to generate the complementary receiver operating characteristic (ROC) curves, and then observe the simulation performances. The threshold λ is set according to [8]:

$$\begin{aligned}\lambda &= F^{-1}(P_f \mid \mu) \\ &= \{x : F(\lambda \mid \mu) = P_f\},\end{aligned} \tag{17}$$

where μ is the degree of freedom, and

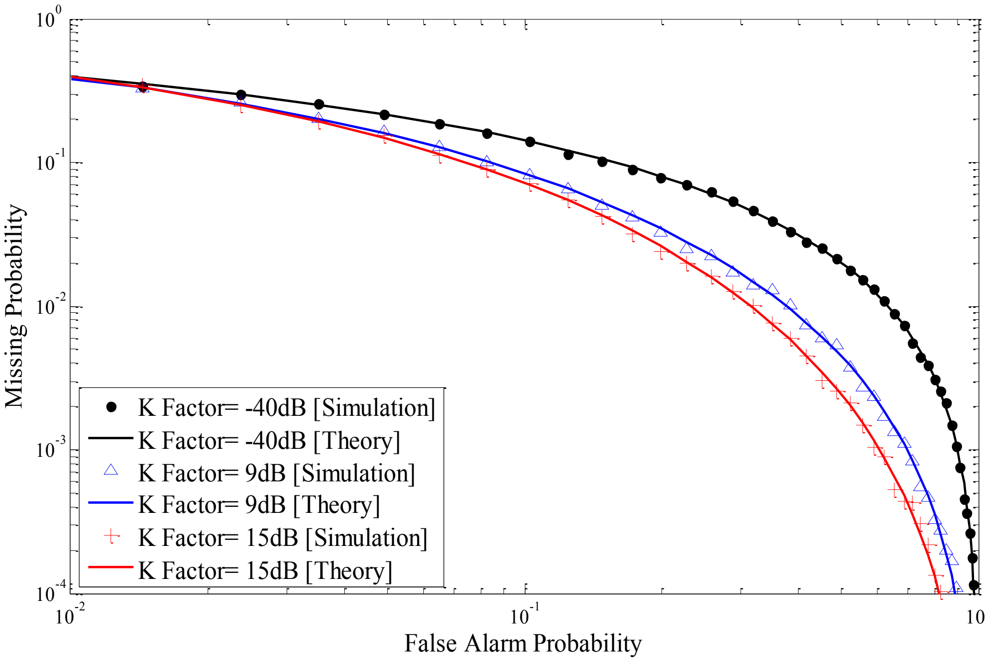

Fig. 6. Complementary ROC curves of the proposed SWDCSS with SNR = 5*dB* under Rician channel with different *K* factor.

$$F(\lambda|\mu)=\int_0^{\lambda}\frac{t^{(\mu-2)/2}e^{-t/2}}{2^{(\mu/2)}\Gamma(\mu/2)}dt. \tag{18}$$

To make the Monte-Carlo simulation results more reliable, we simulate 10,000 spectrum sensing trials, and then average out the simulation results to obtain the final performance curves.

5.2 Simulation Results and Discussion

Fig. 5 and **Fig. 6** shows the performance of the SWDCSS algorithm on different interference and propagation environment. From **Fig. 5**, it is easy to observe that the missing probability P_m decreases as the received SNR increases. It tells that the proposed SWDCSS algorithm performs well in a relative low interference environment. As a result, we set the SNR= 5dB in all simulation scenarios. And we can observe from **Fig. 6** that the missing probability P_m reduces as the K increases, i.e., P_m,(K=−40) > P_m,(K=9) > P_m,(K=15). It indicates that the SWDCSS algorithm performs better with a lager K vaule, which shows the asymptotic behavior as AWGN channel.

Fig. 7 compares the complementary receiver operating characteristic (ROC) curves of our proposed SWDCSS algorithm with the traditional ESCAPE algorithm in [13]. The solid lines represent the theory curves, while the other lines represent the simulation results. From **Fig. 7**, we can observe that the simulation results match the theory curves well. When there is a single SU, the system shows the worst performance due to the lack of information exchange among SUs. It is obvious that both cooperative algorithms, the proposed SWDCSS algorithm

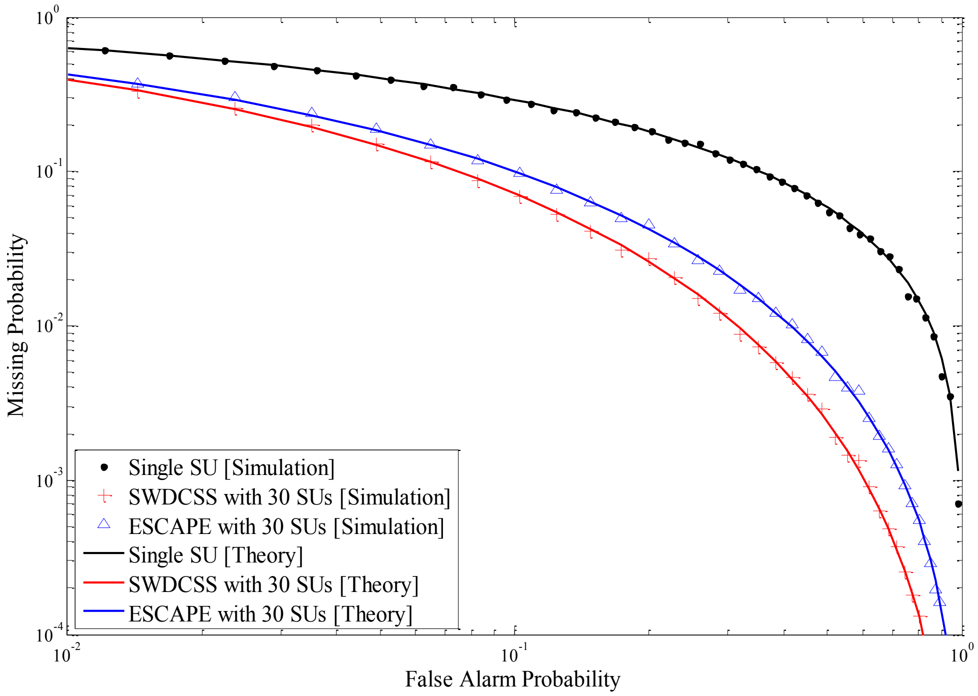

Fig. 7. Complementary ROC curves of the proposed SWDCSS vs. traditional ESCAPE under Rician channel with $K = 15\ dB$.

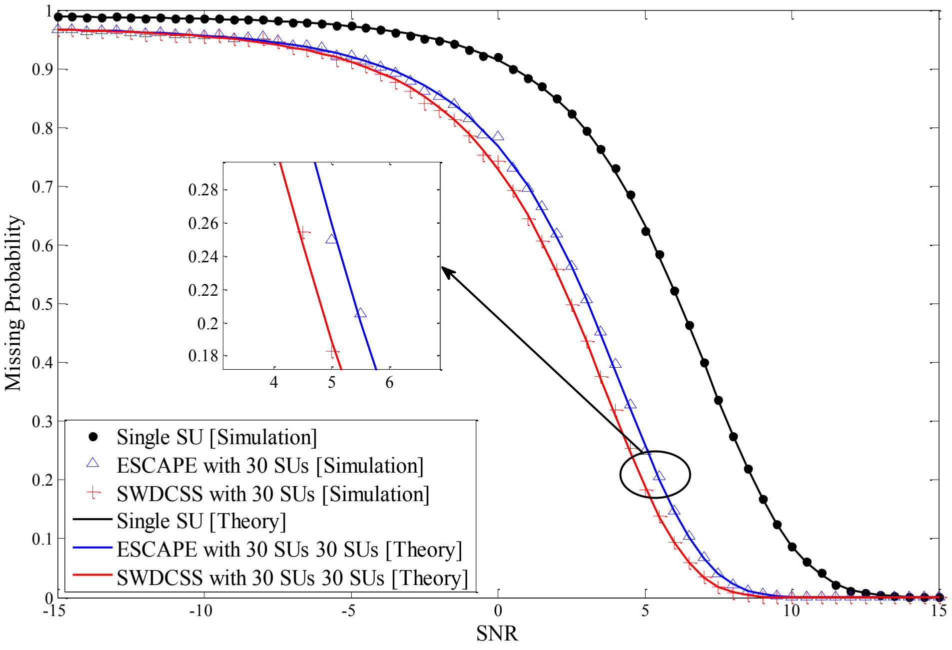

Fig. 8. Missing probability of the proposed SWDCSS vs. traditional ESCAPE under Rician channel with $K = 15\ dB$.

and ESCAPE algorithm, show better performance than the single SU case without cooperation. Furthermore, our proposed SWDCSS algorithm outperforms traditional ESCAPE algorithm since that the weighting factor has been adopted in our algorithm to further reduce the missing probability. As shown in **Fig. 7**, at the target false alarm probability P_f of 0.3184, the proposed SWDCSS algorithm shows the missing probability P_m of 0.0097, while the traditional ESCAPE algorithm shows the missing probability P_m of 0.0185. That is, the proposed algorithm decreases the missing probability by 47.5% compared with the ESCAPE algorithm.

Fig. 8 shows the comparison of missing probability of the proposed SWDCSS algorithm and the traditional ESCAPE algorithm. We expect to reduce the missing probability as low as possible, while keeping the false alarm probability in a relatively low level. For the simulations, we set the false alarm probability P_f equal to 0.1, and try to observe the tendency of missing probability by varying SNR. In **Fig. 8**, we see that the performance of the proposed SWDCSS algorithm is almost overlapped with that of traditional ESCAPE algorithm up to the SNR of -5 *dB*, since that the historical sensing data is not reliable in low SNR range. However, after the SNR of -5 *dB*, the missing probability of our proposed SWDCSS algorithm decreases more rapidly than that of the traditional ESCAPE algorithm, which suggests that the correctness of the sensing results is improved by introducing a proper weighting factor. As shown in **Fig. 8**, when the average received SNR is 5 *dB*, the traditional ESCAPE algorithm shows the missing probability P_m of 0.2530, while our proposed SWDCSS algorithm reaches P_m of 0.1833. That is, the proposed SWDCSS algorithm decreases the missing probability by 27% than the traditional ESCAPE algorithm.

6. Conclusions

In this paper, we propose a SANET-CR system to meet the requirement of growing demands of high data-rate and real-time services in maritime communications. By opportunistically utilizing the spectrum hole of primary network, the spectrum band of SANET can be efficiently expanded. However, SANET may cause unwanted interference to primary network if the active PUs of primary network are not detected due to the hidden primary user problem. To provide an applicable and reliable solution, we propose the self-weighted decentralized spectrum sensing scheme (SWDCSS), which does not need data fusion and prior knowledge of network's topology. In the proposed SWDCSS, a weighting factor has been introduced to improve the correctness of the sensing results. Referring the analytical and simulation complementary receiver operating characteristic (ROC) curves, we observe that by weighting the SUs' local sensing result according to their historical sensing data, the missing probability is significantly decreased and the detection probability is increased compared with the traditional ESCAPE algorithm, i.e., the interference from SANET-CR system to primary network can be dramatically decreased. Furthermore, the false alarm probability is also significantly decreased, which means that the SANET-CR system can use the spectrum hole a lot more reliably.

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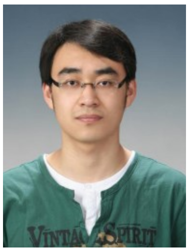

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