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Improved Collaborative Spectrum Sensing Scheme for Maritime Cognitive Radio

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Expeditious growth in wireless networks for numerous wireless services and applications lead to the increase in demand for radio spectrum in both terrestrial and marine wireless communications. Radio spectrum is scarce as the available spectrum is already been allocated to various applications. Cognitive radio technology is an optimistic solution for the spectral scarcity. In Cognitive Radio Networks (CRN), the unused licensed bands are dynamically accessed by the unlicensed secondary users for data transmission. Spectrum Sensing (SS) is the key technique to detect the presence or absence of the primary users. SS for terrestrial wireless communication have been studied vastly. This paper is aimed to study SS for Maritime Cognitive Radio Networks (MCRN) which is daunting as SS in MCRN depends on the sea state. Existing work on SS in MCRN deals with Classical Energy Detection (CED) which is a straight forward procedure with low complexity and can be applied generally to any signal irrespective of its format. Here we intend to perform SS in MCRN using Improved Energy Detection (IED) which surpasses the performance of CED without ruining its general attributes. Evaluations and analysis are carried out using detection probability performance metric for both CED and IED, simulated and compared for different sea states.

[Keywords: Cognitive radio, Energy detection, Maritime communication, Spectrum sensing]

Introduction

Maritime communication with the ship was predominantly using flag semaphores in olden days. It is slowly replaced with wireless radio signals nowadays both for communication from ship to ship and ship to shore. There are existing satellite service systems which supports such communication. Inmarsat, a British telecommunication company based global mobile services, a search and rescue alert satellite system named International Cospas-Sarsat Programme to name a few[1]. Information broadcasting and warning communications during extreme weather conditions such as storms are provided through Very High Frequency (VHF) marine radios worldwide. Wireless services for internet facility for passengers, security, surveillance, control, etc., are expected to improve as demanded by International Maritime Organization (IMO). This improvement requires novel solutions and implementations particularly in terms of coverage and speed, which may enable better wireless access services. However, maritime wireless possesses limited spectrum which prevents accommodating further improvements. This tradeoff can be overcome by using novel technology like cognitive radio for maritime communication[2].

Before the advent of radio, maritime communication was limited to signals that can be seen or heard by humans in the ship or shore. The British Board of Trade formulated the First International Code of Signals which was published in the year 1857. It contained codes for about 70,000 signals[3]. These codes are used internationally for safety and to convey messages in maritime. Guglielmo Marconi invented first operating radio transceiver in 1895. Following that, he transmitted radio messages between two Italian warships at a distance of 22 km outside the port of Spezia in 1897 which brought the revolution in the maritime communication[4]. In those days, marine radio was used mainly to transmit and receive passenger telegrams in the Low Frequency (LF) range which covered only short distance. During 1920, marine radio is advanced with radio telephone technology in High Frequency (HF) range for communication over long distance. Marine VHF radio band was introduced during Second World War for Talk Between Ships (TBS) service which enabled direct bridge to bridge communication between ships. Advancements in electronics technology led to development of various equipment, devices and marine radar. In 1959, International Maritime Organization (IMO) developed regulations for improving sea safety that are followed by all shipping nations[1]. The principal vision of IMO is to facilitate safe and secure navigation, vessel traffic observation and efficient data exchange among the vessels. Inmarsat was established by IMO in 1979 to enable long distance communication to the vessels that are very distant from the sea shore. IMO developed worldwide integrated systems, namely, Global Maritime Distress and Safety System (GMDSS) and International Convention on Maritime Search and Rescue (SAR) to respond any emergency in the ship. SAR is a global system that responds to emergency at sea whereas GMDSS provides efficient communication support during emergency.

Networks, technologies and related works for maritime communication

Maritime networks are mainly based on HF, VHF and UHF radios for communication for the ships near the shore. Capacities of these bands are small and they support only simple and basic services such as surfing, messaging and mail communication. For long distance communications between multiple ships and ship to shore, satellite systems are used which are expensive due to cost of launching satellite in the orbit and installing antenna stabilizer on the ship. Rapid growth in maritime industry increases the demand for high speed and affordable communication. Hence lots of research works are aiming at the development of new technologies and wireless networks to meet the requirements of maritime communication. High speed and long-distance terrestrial communication provided by WiMAX – wireless mesh networks following IEEE 802.16e standard is extended to maritime communication. Wireless-broadband-access for SeaPort (WISEPORT) is the first maritime wireless mesh network based on WiMAX which is launched in Singapore which offers low cost high bandwidth seamless mobile connectivity and covers the distance of 15 km[5]. Digital VHF radio was proposed in Norway with the date rate of 21 kb/s and 133 kb/s[6]. Tri-media Telematic Oceanographic Network (TRITON) was developed which follows 802.16d standard with the data rate of 6Mb/s and the coverage distance of 35.3 km[7].

Despite development of many systems and networks to provide better data, long distance communication and quality of service maritime communication finding dedicated bandwidth for high speed maritime communication is difficult due to congested bandwidth. Hence cognitive radio is introduced to marine communication to access the spectrum dynamically. Cognitive radio networks enable the unlicensed secondary user to dynamically access the band of licensed primary user without interference in the primary user signals. Maritime Cognitive Radio Network (MCRN) is proposed to overcome the challenges of maritime communication by exploiting the unused licensed bandwidth[2]. Spectrum holes in the licensed bandwidth are detected by spectrum sensing function of cognitive radio. In MCRN environment, spectrum sensing function highly depends on the nature of the sea state, as the movement of ship causes movement in the antenna which degrades the communication. In literature, spectrum sensing detectors are studied vastly for terrestrial environment[8]. Some of the popular detectors are energy detector[9], matched filtering based detector[10], cyclostationary feature based detector[11], covariance detector[12], multi taper spectrum detector[13], filter bank based detector[14], cooperative sensing detector techniques[15], etc. Research works on spectrum sensing in MCRN are relatively less when compared to terrestrial CRN. The authors[16] proposed an algorithm based on energy detection in order to reduce energy consumption for spectrum sensing in cooperative MCRN. An optimal entropy based spectrum sensing technique in cooperative MCRN is proposed[17]. CR in maritime AIS network and spectrum sensing is carried out using energy detection by Tang *et al.*[18]. In energy detection method, energy of the received signal at specific frequency band is calculated and compared with the decision threshold. The occurrence of primary user is declared if the signal energy exceeds the decision threshold value. Else, the primary user is declared absent and the secondary user can access that band. This Classical Energy Detection (CED) does not need prior information about the primary user, so that it can be applied generally to any signal irrespective of their format. Among all other techniques CED is widely used in literature owing to its low complexity and general applicability. Other spectrum sensing techniques require the knowledge of primary user's signal and are computationally complex but they outperform CED. Improved Energy Detection (IED) technique can improve the performance of CED while preserving its low complexity and general applicability[19]. In this paper, the aim is to analyze the spectrum sensing performance using IED in MCRN for different sea states.

Cognitive radios are intelligent transceivers designed to exploit unutilized licensed spectral bands in a dynamic fashion. Its primary functionality is to detect whether a licensed spectrum is free or occupied temporally, which is referred to as spectrum sensing. If identified to be unoccupied, then cognitive radios utilize the idle spectrum for its communication. Various techniques to perform spectrum sensing are matched filter detection, energy detection and feature detection. Among all, energy detection process is considered very popular, for which prior knowledge regarding the nature of the licensed user is not necessary. Originally proposed for terrestrial communication, the idea of cognitive radios can be extended to maritime communication as well in which the maritime wireless services in ships are considered as cognitive radio users. As the maritime channel is found to be varying depending on the sea conditions, the task of detecting the spectrum availability by maritime cognitive radio is very challenging. This paper proposes an improved detection technique considering cognitive maritime users.

Materials and Methods

Maritime cognitive radio networks and channel modeling

Two different categories of MCRN are

- Ship - ship network and ship-shore network close to the sea shore
- Ship - ship deep sea adhoc network using satellite support link as shown in Figure 1.

All the ships are equipped with the hardware and software that are necessary to carry out cognitive radio functions. They perform spectrum sensing in radio environment periodically to gain spectrum access when PU is absent. Ships that are far away from the shore gain access to the fusion center using the satellite link. Besides the terrestrial cognitive radio network features, ship as a cognitive radio is expected to change its factors according to nature of the sea state, geographic position and the number of nodes. The sea surface is flat and there is no path loss. The interference among the line of sight path and the signal reflected path results in path loss[20].

Sea motion

It is fundamental to consider the generation of arbitrary sea surface for the propagation analysis of MCRN. General condition of surface of the open sea is described by sea states. Sea state is defined by integrated wave parameters such as wave height and

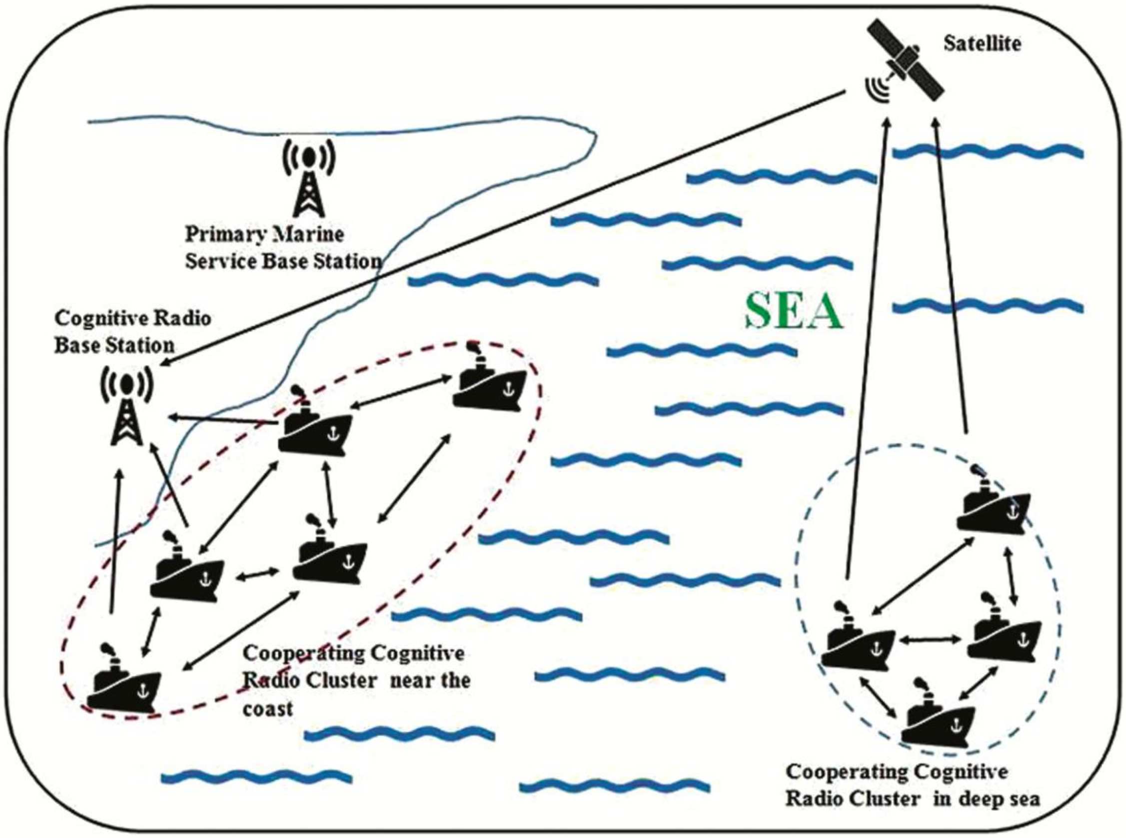

Fig. 1 — Illustration of maritime cognitive radio network architecture

wave period. Physical condition of the sea is classified into 10 levels as described by Pierson-Moskowitz[21]. World Maritime Organization (WMO) defines sea state codes as given in the Table 1.

Channel model

Channel model in marine environment is different as that of channel model in terrestrial environment. The signal strength decays along the path as the surface of the sea behaves as a reflector for radio wave propagation. In terrestrial environment, signals in the communication channel are affected by phenomenon such as diffraction, scattering, reflection and refraction. The pathloss in terrestrial environment is given by Elliott[22] as

$$PL_T(d) = PL_T(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + X_f^T \qquad \ldots (1)$$

Where, PL_T is the pathloss measured at a reference location d_0, d is the actual transmitter-receiver range, α is the environment's free space exponent factor modeling the path loss and X_f^T is a Gaussian random noise with zero mean and standard deviation σ_t which represents effects due to fast fading. Communication channel characteristics highly depend on the pathloss exponent which varies in value between 1 and 4 and depends on the physical terrain's characteristics.

The pathloss value in marine communication channel intensifies as sea state increases. The pathloss in marine communication channel under shadowing effects is given as a function of wave height[23] as below

$$P_l(h, f_o) = P_l(d_r) + 10\left\{\left(0.498\log_{10}(f_o) + 0.763\right)h + 2\right\}\log_{10}(d/d_r) + N_{f_o} \qquad \ldots (2)$$

Where, f_0 is the frequency (Giga Hertz), h is the noticeable sea height in meters, and N_{f_o} is a random variable with zero mean and standard deviation σ_f, which is also represented as a function of wave height and is given by

$$\sigma_{f_o} = \left(0.157 f_o + 0.405\right) * h \qquad \ldots (3)$$

Table 1 — Codes for sea state defined by WMO

Code	Wave height (m)	Characteristics
0	0	Calm (mirror/glassy)
1	0 to 0.1	Calm (rippled nature)
2	0.1 to 0.5	Smooth (wavelets/glassy)
3	0.5 to 1.25	Slight (small waves)
4	1.25 to 2.5	Medium (moderate waves)
5	2.5 to 4	Rough (large waves)
6	4 to 6	Very rough (moderately high)
7	6 to 9	High (very high waves)
8	9 to 14	Very high (exceptionally high)
9	> 14	Phenomenal (spray & foamy)

Spectrum Sensing in MCRN

This paper considers the PU spectrum in the VHF band with a carrier frequency of 161.975 MHz which is used in maritime cognitive radio AIS (Automatic Identification System)[18]. Every SU ship in MCRN satisfies all the requirements of cognitive radio including spectrum sensing capability and reconfigurability. System model with N SUs is considered for performance analysis. The base station for maritime communication is situated at the sea shore which is considered to be the fusion center. It is assumed that each SU makes use of finite number of samples denoted by M for spectrum sensing. The signal transmitted by the PU is given by

$$x(t) = \mathrm{Re}\left\{s(t)e^{j(2\pi f_c t+\theta)}\right\}^{\text{(ref. 17)}} \qquad \ldots (4)$$

Where, $s(t)$ is a complex natured baseband signal with bandwidth B, carrier frequency f_c, and initial phase angle θ. For simplification of analysis process, only the real part of the signal was considered. The signal received by SU is referred to as $r(t)$ and expressed as

$$x(t) = \mathrm{Re}\left\{s(t)h_c(t)e^{j(2\pi f_c t+\theta)}\right\} + w(t) \qquad \ldots (5)$$

Where, $h_c(t)$ is the baseband channel model and $w(t)$ is the Additive White Gaussian Noise (AWGN) added in the channel. The received signal at the SU after experiencing path loss as in equation (2) is given by

$$\psi(t) = \mathrm{Re}\left\{s(t)\sqrt{\frac{G}{PL_M}}e^{j2\pi f_c t+\varphi}\right\} + w(t) \qquad \ldots (6)$$

Where, G is the gain of the antenna in dB.

The following equation shows the SU spectrum sensing binary hypothesis model to detect the absence or presence of PU.

$$r(t) = \begin{cases} w(t), & \text{under } H_0 \\ \psi(t) + w(t), & \text{under } H_1 \end{cases} \qquad \ldots (7)$$

Where, H_0 equals the hypothesis corresponding to idle channel condition and H_1 to the hypothesis corresponding to busy channel. Practically, spectrum sensing leads to detection error which can be modeled as false alarm rate and missed detection rate. When the cognitive user founds that the spectrum is occupied when it is actually unoccupied, a false alarm is said to have occurred. False alarm lowers the spectrum utilization opportunity for the SU. Alternatively, when the SU decides that the spectrum is unoccupied when it is actually occupied by the PU, a missed detection is said to have occurred. Missed detection causes harmful interference to the PU. Fundamentally, the performance investigations of spectrum sensing is carried out using the probability of detection P_d or its complementary probability of missed detection P_md and the probability of false alarm P_f. It is expected that for a better performance, P_d should be high and P_f should be low. The detection and false alarm probabilities in general form are given by

$$P_d = P\left(\varphi\left(r_n\right) > \lambda / H_1\right) \qquad \ldots (8)$$

$$P_f = P\left(\varphi\left(r_n\right) \leq \lambda / H_1\right) \qquad \ldots (9)$$

Where, λ is a preset value of decision threshold and $\varphi(r_n)$ is the decision statistic of the spectrum sensing algorithm.

Classical Energy Detection (CED)

Spectrum sensing using CED is the simplest detection technique which operates with no knowledge about the licensed user signal. The important parameters for CED are detection threshold λ, number of samples M, and estimated noise power. The signal energy received at the SU is estimated over M number of samples given by

$$\varphi_i\left(r_i\right) = \sum_{n=1}^{M}\left|r_i\left(n\right)\right|^2 \qquad \ldots (10)$$

Where, ϕ_i refers to the test static calculated at i^th sensing instant and n is the number of samples which varies from 1 to M and over which the energy is calculated. The detection and false alarm probability for CED under AWGN channel is considered as given by Lopez-Benitez & Casadevall[19]

$$P_d^{CED} = Q\left(\frac{\lambda - M\left(\sigma_x^2 + \sigma_w^2\right)}{\sqrt{2M}\left(\sigma_x^2 + \sigma_w^2\right)}\right) \qquad \ldots (11)$$

$$P_f^{CED} = Q\left(\frac{\lambda - M\sigma_w^2}{\sqrt{2M}\sigma_w^2}\right) \qquad \ldots (12)$$

Where, σ_x^2 is the average received power of the signal, σ_w^2 is the AWGN noise variance and the function $Q(.)$ is the tail probability of the standard normal distribution. From equation (12) the threshold can be expressed as

$$\lambda = \sigma_w^2\left(Q^{-1}\left(P_f^{CED}\right)\sqrt{2M} + M\right) \qquad \ldots (13)$$

Substituting equation (13) in (11), the probability of detection is given in terms of SNR as

$$P_d^{CED} = Q\left(Q^{-1}\left(P_f^{CED}\right) - \sqrt{\frac{M}{2}\gamma}\right) \qquad \ldots (14)$$

Where, γ is the SNR in dB which is given by $\gamma = \frac{\sigma_x^2}{\sigma_w^2}$

Improved Energy Detection (IED)

IED improves the performance of CED detection by avoiding any missed detection caused due to drop in the instantaneous energy[18]. IED computes the test static similar to CED but the difference is that it keeps up a buffered list of decision statistic of the previous L sensing instant values. It then computes the average test statistic value as given by

$$\varphi_i^{avg}\left(\varphi_i\right) = \frac{1}{L}\sum_{n=1}^{L}\varphi_{i-L+1}\left(r_{i-L+1}\right) \qquad \ldots (15)$$

Where, L refers to the configurable parameter of the algorithm and $\varphi_i^{avg}\left(\varphi_i\right)$ is the mean value of decision statistic computed at the i^th instant which depends on the past test statistic values. If the test statistic $\varphi_i\left(r_i\right)$ falls below the decision threshold λ, an extra comparison based on $\varphi_i^{avg}\left(\varphi_i\right)$ is performed. If $\varphi_i^{avg}\left(\varphi_i\right)$ again falls below λ, a final comparison with the previous sensing instant's test statistic $\varphi_{i-1}\left(r_{i-1}\right)$ is made. When the test statistic in both the additional check is greater than the decision threshold the spectrum is declared busy. Otherwise, the channel is confirmed idle and then the SU can access the PU's band. The block diagram of the proposed IED algorithm with cooperative sensing is illustrated in Figure 2. Cooperative sensing is explained in the following section. Algorithm for IED is given in Table 2.

The probabilities of detection and false alarm for IED are given by Tang[18],

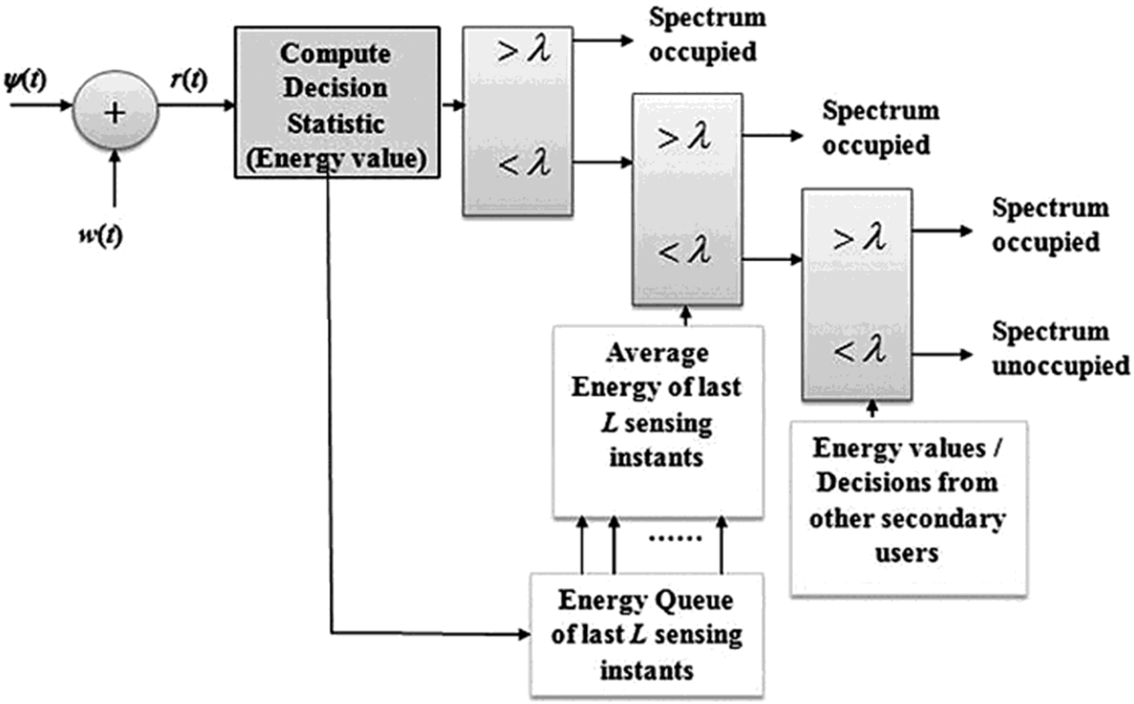

Fig. 2 — Block diagram of proposed IED algorithm with cooperative sensing

Table 2 — Algorithm for IED

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Input: $\lambda \in \mathbf{R}^{+}, M \in \mathbf{N}, L \in \mathbf{N}$
Output: $S_i \in \{H_0, H_1\}$
for every sensing instant i do
    $\varphi_i(r_i) \leftarrow$ compute energy
    $\varphi_i^{avg}(\varphi_i) \leftarrow$ compute average of
        $\left(\varphi_{i-L+1}(r_{i-L+1}), \varphi_{i-L+2}(r_{i-L+2}), \ldots\ldots\varphi_{i-1}(r_{i-1}), \varphi_i(r_i)\right)$
    if $\varphi_i(r_i) > \lambda$, then
        $S_i \leftarrow H_1$
    else
    if $\varphi_i^{avg}(\varphi_i) > \lambda$, then
    if $\varphi_{i-1}(r_{i-1}) > \lambda$, then
        $S_i \leftarrow H_1$
    else
        $S_i \leftarrow H_0$
```

$$P_d^{IED} = P_d^{CED} + P_d^{CED}\left(1 - P_d^{CED}\right) Q\left(\frac{\lambda - \mu_{avg}}{\sigma_{avg}}\right) \quad \ldots (16)$$

$$P_f^{IED} = P_f^{CED} + P_f^{CED}\left(1 - P_f^{CED}\right) Q\left(\frac{\lambda - \mu_{avg}}{\sigma_{avg}}\right) \quad \ldots (17)$$

Where, λ is the threshold value for IED which depends on P_f^{IED}. σ_{avg} and μ_{avg} are the standard deviation and mean of $\varphi_i^{avg}(\varphi_i)$, assuming that the average test statistic value is normally distributed.

$$\mu_{avg} = \frac{J}{L} M\left(\sigma_x^2 + \sigma_w^2\right) + \frac{L-J}{L} M\left(\sigma_w^2\right) \quad \ldots (18)$$

$$\sigma_{avg}^2 = \frac{J}{L^2} 2M\left(\sigma_x^2 + \sigma_w^2\right)^2 + \frac{L-J}{L^2} 2M\left(\sigma_w^4\right) \quad \ldots (19)$$

Where, $J = [0,L]$ is the total number of sensing instants in which the PU's signal is actually present. It is difficult to assume the actual value of N in practice. It is only known that the output decisions H_0 / H_1 does not certainly imply the presence or absence of PU. Hence the performance of IED cannot be exactly projected in practice as it relies on the PU's spectrum occupancy. However, it is possible to analyze the algorithm for the two extreme cases, namely, the lower and upper bounds as given below.

Case 1: $J = 0$, when the channel is always idle for the last L sensing events.

Case 2: $J = L$, when the channel is always busy for the last L sensing events.

Cooperative spectrum sensing and detection

Spectrum sensing with multiple SUs cooperatively improves the performance of sensing in MCRN. All the SUs in the MCRN perform spectrum sensing and their local decisions are forwarded to the centralized fusion center. Cooperative detection at the base station or fusion center is based mostly on the common fusion rules namely AND rule, OR rule and *K*-out-of-*N* rule. Fusion center then forwards the cooperative decision regarding the occurrence of the PU to all the individual SUs[15]. The detection and false alarm probability for *K*-out-of-*N* rule which is the generalized form of fusion rule are given by

$$\Theta_d = \sum_{b=K}^{N} \binom{N}{b} \left(P_d^{IED}\right)^b \left(1-P_d^{IED}\right)^{N-b} \text{ (ref. 16)} \qquad \ldots (20)$$

$$\Theta_f = \sum_{b=K}^{N} \binom{N}{b} \left(P_f^{IED}\right)^b \left(1-P_f^{IED}\right)^{N-b} \text{ (ref. 16)} \qquad \ldots (21)$$

Where, Θ_d and Θ_f are the global or total probability of detection and the global or total probability of false alarm, *b* is the number of SUs reporting the presence of PU and *m* is the total number of SUs participating in the cooperation.

Results and Discussion

The simulation and analysis for MCRN is carried out using MATLAB for various sea wave conditions and pathloss model. In this section the performance comparisons of CED and IED for spectrum sensing in MCRN are presented. Here single band spectrum sensing is considered and hence considered single PU for simulation. In particular VHF frequency band at 161.975 MHz is used which is used in maritime cognitive radio AIS[17]. The bandwidth occupied by the signal is assumed as 12.5 kHz. It is assumed that the SU does not know about PU's position, velocity or the direction of movement.

Pathloss for marine environment at sea states 2, 4, 6 and 7 are simulated and compared with the path loss simulated for terrestrial environment as shown in Figure 3. The transmitter-receiver range is made to vary from 0 to 20 km and the reference distance is set to 1 m. The simulation results illustrate that the pathloss at sea states 2 and 4 are close to the pathloss at terrestrial. Pathloss becomes severe when the sea state characteristics become aggressive. Path loss at sea state 6 is twice as that of sea state code 4 and at sea state code 7, the path loss is four times than that of sea state 4. According to the energy efficient spectrum sensing algorithm proposed[15] the SU do not perform spectrum sensing when the sea state code reaches 7. It is because as the sea state increases beyond 7, harmful interference is caused to PU as the detection performance becomes poor. It is also observed that at sea states 7 and above, the sensing time to detect PU increases which consumes more energy. Hence this paper deal only with sea states 2, 4 and 6 for performance analysis.

For all simulations, the case that the channel is always busy for all *L* sensing events is considered *i.e.* $J = L$, because when $J = 1$, CED and IED methods are identical. When *L* is increased φ_i (r_i) can be estimated more accurately which leads to improvement in P_d^{IED}. Also there is a tradeoff between the achieved performance gain and the storage memory required to hold the past decision statistic values. Hence the optimal value for *L* is chosen as 5. The probability of false alarm is supposed to be chosen not greater than 10^{-1} according to the IEEE 802.22 specification standard[15]. Hence the decision threshold for CED and IED is set to maintain P_f^{CED} =10^{-1} and P_f^{IED} =10^{-1}.

The probability of detection is calculated for both CED and IED in the SNR range from -15 to 5 dB over the fixed number of samples $M = 1000$. P_f^{CED} and P_f^{IED} are fixed at 10^{-1} according to the requirement of IEEE 802.22 standard. Figure 4 show the plots of detection probability against SNR for terrestrial and sea states 2, 4 and 6 using CED and IED. It is shown that at lower sea state 2 and 4, the probability of detection of IED is higher than

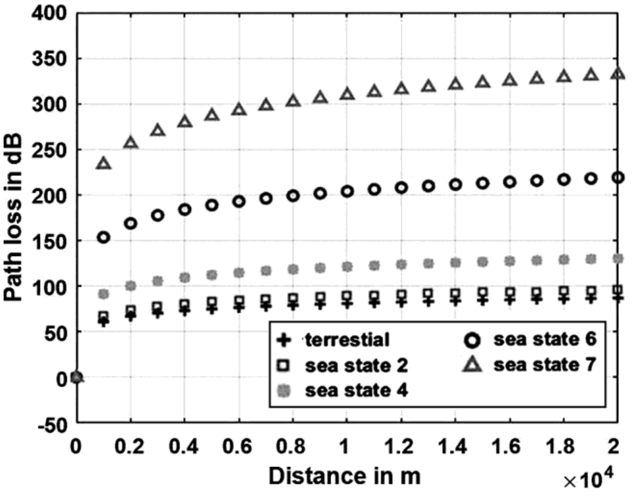

Fig. 3 — Pathloss at frequency 161.974 MHz for terrestrial and sea states 2, 4, 6 and 7

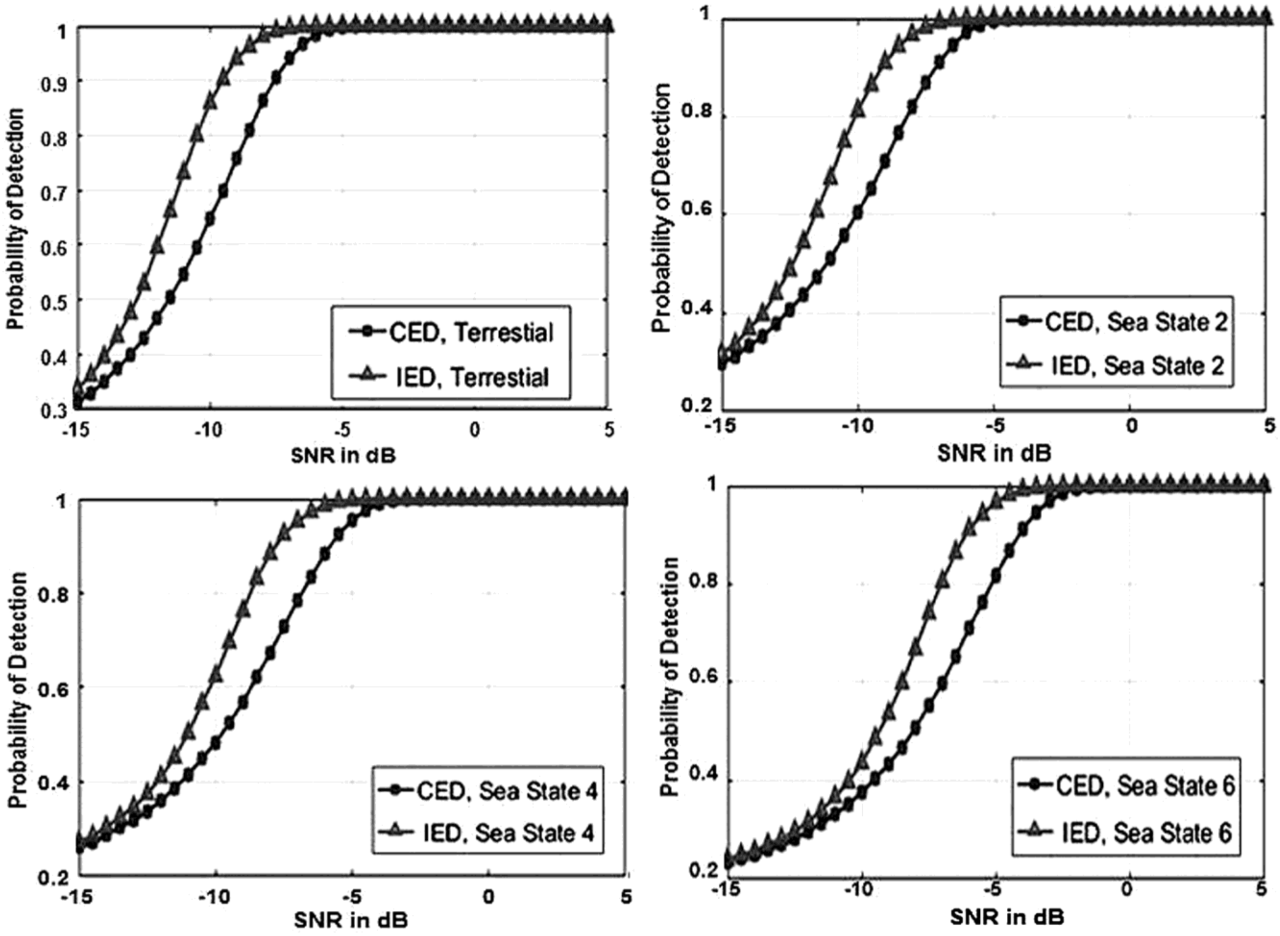

Fig. 4 — Probability of detection versus SNR for CED and IED

probability of detection of CED in the SNR range -15 to -5 dB and both are almost equal in the SNR range -5 to 5 dB. For higher sea state 6 the improvement is in the SNR range -12.5 to -2.5 dB. This implies that IED can perform better than CED for the signals with low SNR (*i.e*. the PU signal can be detected efficiently even when the noise power is more) even in the higher sea states. In particular, the performance improvement of IED over CED is quantified for SNR = -10 dB and is tabulated in Table 3.

Receiver Operating Characteristics (ROC) curves are essential to investigate the performance of any hypothesis testing problem. It is the plot of probability of detection against probability of false alarm at any specific SNR value. From Figure 3, it is evident that IED performs better than CED at SNR = -10dB for terrestrial and sea states 2, 4 and 6. Hence we consider SNR as -10 dB for simulating ROC. The probability of detection is calculated for every probability of false alarm value in the range 0 to 1. Figure 5 shows the ROC for CED and IED at terrestrial and sea states 2, 4 and 6, respectively. The probability of detection if found to increase with probability of false alarm. The ROC performance of IED is better than CED for all the sea states (IED shows better performance even at higher sea state). Also Figure 6 shows the global ROC for CED and IED for cooperative detection using *K* out of *N* logic rule at terrestrial and sea state codes 2, 4 and 6, respectively. The performance improvement is evident using cooperative sensing.

Table 3 — Performance improvement

State	P_d (CED)	P_d (IED)	% Improvement
Terrestrial	0.64	0.87	35.94
Sea state 2	0.6	0.81	35.00
Sea state 4	0.48	0.62	29.16
Sea state 6	0.38	0.43	13.16

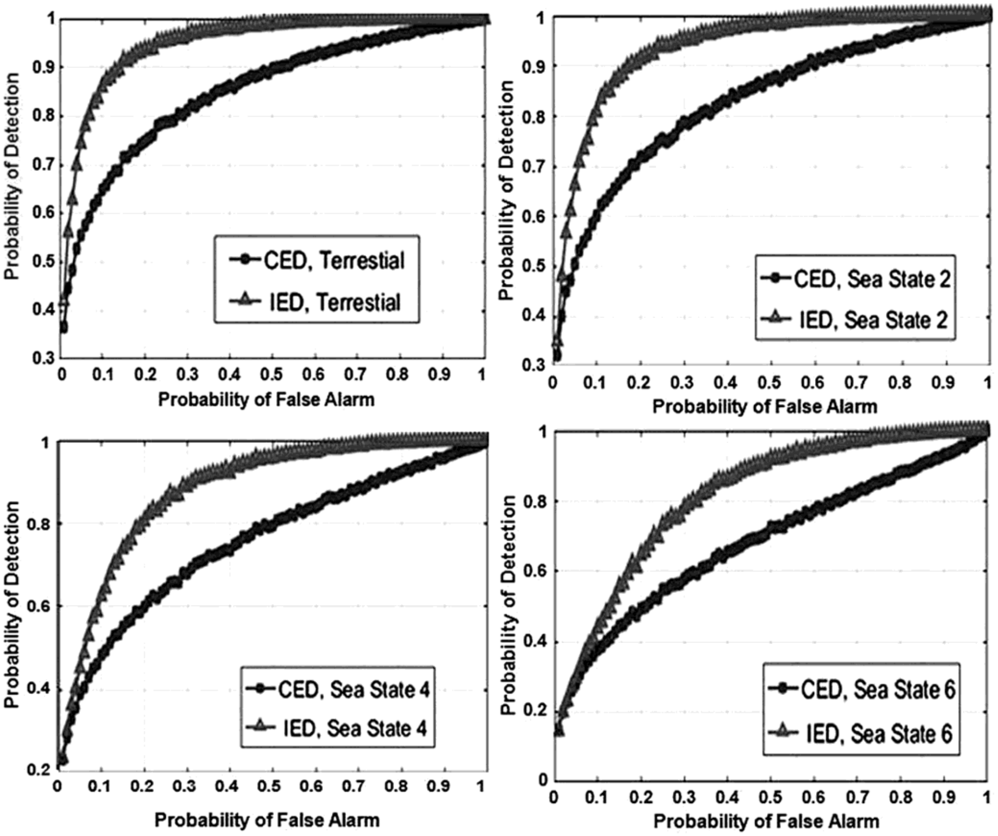

Fig. 5 — ROC performance for CED and IED

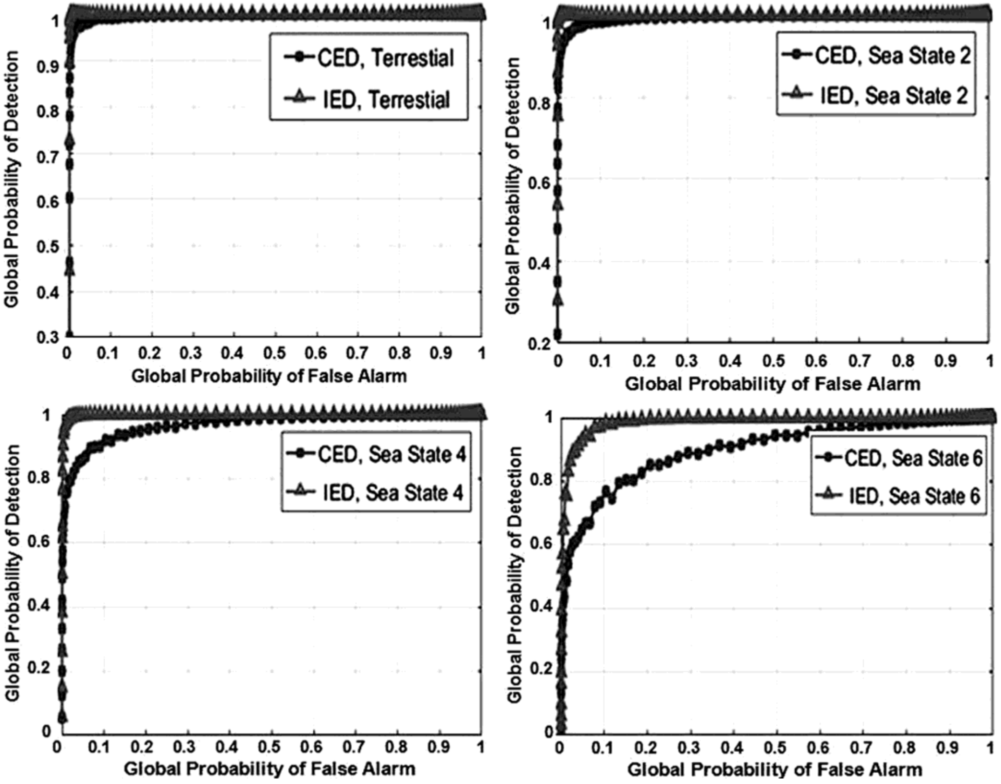

Fig. 6 — ROC performance for CED and IED under cooperative sensing

Conclusion

The principal motive of this paper is to perform efficient spectrum sensing in MCRN for different sea states. Spectrum sensing through energy detection is a well-received technique as it is simple and do not require the prior knowledge about PU signal. IED is the improved version of CED which is used in this paper to perform spectrum sensing in MCRN. The ROC performance of CED and IED are simulated and the results are compared. IED outperforms CED in all sea state conditions considered for simulations and also IED enhances the probability of detection even in the lower SNR region.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contributions

KM contributed in conceptualization, algorithm development and analysis. RH and SR contributed in algorithm development. All the authors contributed in writing and revision of the manuscript.

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