

Performance Analysis of Local and Cooperative Spectrum Sensing in Cognitive Radio Networks

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Abstract

Cognitive radio (CR) has recently been identified as a promising technology to solve the spectrum inefficiency problem. CR users or secondary users (SUs) need to sense the presence of primary users (PUs) constantly and rapidly to utilize their unused spectrum. However, detection is compromised when a user experiences shadowing or fading effects. In such cases, the user cannot distinguish between an unused band and a deep fade. So, cooperative spectrum sensing is proposed to improve sensing performance. In this paper, we analyze the different spectrum sensing schemes with different fusion rules and their comparative behavior has also been studied. Moreover, the relationship between the throughput and sensing time in local and cooperative spectrum sensing has been investigated for PU protection and SU spectrum utilization mode. We also observe that average channel utilization depends on the number of cooperative users under PU protection scenario. The analytical results show that cooperative spectrum sensing employing OR rule has better performance than other fusion rules as well as non-cooperative scheme.

Keywords: *Cognitive Radio, Spectrum Sensing, Hard Fusion Rules, Energy Detection, Spectrum Utilization*

1. Introduction

Radio spectrum is a very important and limited resource for wireless communication systems. Recently, CR technology has been proposed as a promising solution for improving the efficiency of spectrum usage by adopting dynamic spectrum resource management concept. CR technology allows the CR users or SUs to share the spectrum with PUs without causing any harmful interference to the PUs. Therefore, spectrum sensing is a critical issue of CR technology since it needs to detect the presence of PUs accurately and swiftly. Therefore, the SUs are required to periodically monitor the PUs activities using fast and reliable sensing schemes. Existing spectrum sensing techniques can be divided into three types [1]: energy detection, matched filter detection and cyclo-stationary detection. In this work, we consider energy detection method which is the most common and simplest as well as it does not need any prior information about the PUs signals. Moreover, energy detection method has been thoroughly studied both in local spectrum sensing [2-4] and cooperative spectrum sensing [5-8]. In cooperative spectrum sensing, local spectrum sensing information from multiple CRs are combined for PU detection. In a centralized CR network, a common receiver plays a key role in collecting this information and detecting spectrum holes [6]. Cooperative spectrum

sensing was proposed to overcome noise uncertainties, fading and shadowing in PU signal detection. It can be a solution to hidden node problem and decrease sensing time as well [9]. There are two key probabilities for spectrum sensing: detection probability and false alarm probability. False alarm probability (P_f) denotes the probability of a CR user declaring that a PU is present when the spectrum is actually free whereas probability of detection (P_d) denotes the probability of a CR user declaring that a PU is present when the spectrum is indeed occupied by the PU [10]. High detection probability is always required to ensure minimum level of interference to PUs. Low probability of false alarm should be targeted to offer more chances for SUs to use the sensed spectrum. In this paper, the relationship between throughput and sensing time has been analyzed for local and cooperative spectrum sensing. In cooperative sensing, several SUs cooperate together to come out with a final decision on the presence of PUs. Cooperative spectrum sensing improves the detection performance as well as tackles the hidden terminal problem. Each of the CR users senses the presence of a PU in a channel and sends their sensing information in the form of 1-bit binary decision (1 or 0) to Fusion center (FC). The hard decision combining rule (OR, AND) is performed at FC using a counting rule to make the final decision regarding whether the PU is present or not [11-13]. In local sensing, a SU makes an individual decision on PU's presence. In this work, spectrum utilization is analyzed under two schemes, namely, PU protection and SU spectrum usability modes. This paper helps us to understand the optimal sensing time for performance improvement in CR networks. So, the main contributions of this paper are summarized as follows:

1. We show that cooperating sensing outperforms local sensing in terms of channel utilization.
2. We analyze the system performance when the detection probability or false alarm is fixed considering PU protection mode and SU utilization mode.

The rest of this paper is organized as follows. In Section 2, we review the local spectrum sensing scheme and the cooperative spectrum sensing is presented using fusion schemes in Section 3. In Section 4, spectrum utilization schemes are presented. The analytical results are presented in Section 5. Finally, we draw our conclusion in Section 6.

2. Local Spectrum Sensing Scheme

In CR communication, spectrum sensing is a key element as it must be performed before allowing unlicensed users to access a vacant licensed band. In local spectrum sensing, each SU makes its own sensing decision on the presence of PUs. The goal of spectrum sensing is to detect the presence of PU signal confined inside some a priori known bandwidth B . However, to detect the presence or absence of PU signal the binary testing hypothesis problem can be written as follows:

$$\begin{aligned} H_0 : x(n) &= v(n), \text{ if primary user is absent} \\ H_1 : x(n) &= s(n) + v(n), \text{ if primary user is present} \end{aligned} \quad (1)$$

where $n=1,2,3..N$ and N is the number of samples. Hypothesis H_0 states that the received baseband complex signal $x(n)$ contains only additive white Gaussian noise (AWGN) $v(n)$ when the PU is absent. On the contrary, hypothesis H_1 states that $x(n)$ consists of a primary signal $s(n)$ corrupted by $v(n)$ when PU is present. P_s is the average signal power of a PU. The

noise $v(n)$ is assumed to be AWGN with zero mean and variance σ_v^2 . The goal of the local spectrum sensing is to reliably decide on the two key probabilities: the high P_d and the low P_f . In this work, we use the radiometer technique known as energy detection which is the most common way of spectrum sensing because of its low computational and implementation complexities. In addition, it is more generic as SU receivers do not need any prior knowledge on the PU's signal. We assume energy detector [2] is applied by each CR user. The energy detector consists of a square law device followed by a finite time integrator. The output of the integrator at any time is the energy of the input to the squaring device over the interval. The noise pre-filter is used to limit the noise bandwidth. The noise at the input to the squaring device has a band-limited, flat spectral density. The decision statistic t for energy detector is given by

$$t = \sum_{n=1}^N x(n) \quad (2)$$

It is well known that under the Neyman-Pearson detection performance criteria, the likelihood ratio yields the optimal decision. Hence, the energy detection performance can be characterized by a resulting pair of P_f and P_d (P_f, P_d) that is estimated as

$$\begin{aligned} P_f &= P(t > \gamma / H_0) \\ P_d &= p(t > \gamma / H_1) \end{aligned} \quad (3)$$

where γ is a particular threshold that tests the decision statistics. $Q(x)$ is the tail of a zero-mean unit variance Gaussian random variable. The test statistics chi-square distribution can be approximated as Gaussian based on the central limit theorem. Then equation (3) can be written as follows

$$\begin{aligned} P_f &= Q\left(\frac{\gamma - N\sigma_v^2}{\sigma_v^2 \sqrt{2N}}\right) \\ P_d &= Q\left(\frac{\gamma - N\sigma_v^2 - NP_s}{\sigma_v \sqrt{(2N\sigma_v^2 + 4NP_s)}}\right) \end{aligned} \quad (4)$$

It is easy to see that in order to ensure a particular operation point (P_d, P_f), the required number of samples N is given by

$$N = 2 \left[Q^{-1}(P_f) - Q^{-1}(P_d) \sqrt{(1 + 2SNR)} \right]^2 SNR^{-2} \quad (5)$$

where signal to noise ratio $SNR = P_s / \sigma_v^2$. Spectrum availability for the opportunistic spectrum access may be determined by direct spectrum sensing. Moreover, in the normal operation mode, the SU has to detect the channel periodically during its data transmission to decide whether the channel is idle or not. After detecting a white space, the SU starts to utilize it by properly tuning its transmission parameters. However, SUs should periodically sense the licensed spectrum in case a PU starts to transmit. Secondary system is able to monitor the frequency band and make a decision in every L (sensing duration) seconds about the presence of PUs. Based on this consideration, we can define two different scenarios: (1) the PU protection mode and (2) the SU protection mode. The PU protection mode is viewed from PU's perspective. It guarantees a minimum level of interference to PUs. This scenario

can be realized by fixing P_d at the required level and minimizing the P_f as much as possible. Thus, P_f can be derived as

$$P_f = Q\left(SNR \times \sqrt{\frac{N}{2}} + Q^{-1}(P_d)\sqrt{1+2SNR}\right) \quad (6)$$

The second scenario is taken from the SU's perspective. It aims to standardize the spectrum utilization by SU. According to the standard's requirements, the P_f values should be fixed at lower values while keeping P_d maximum. Therefore, P_d can be written as follows

$$P_d = Q\left(\frac{Q^{-1}(P_f) - SNR \times \sqrt{\frac{N}{2}}}{\sqrt{1+2SNR}}\right) \quad (7)$$

3. Cooperative Spectrum Sensing Scheme

This section presents the cognitive radio network model using some well known fusion schemes. Hard Decision Fusion means that each SU observes the signal energy in a given spectrum band, compares it to a threshold and makes a decision on the presence of a PU according to the observation. Then, each cooperative node shares its decision with other radios using zero or one to inform whether they observe a free channel or an occupied channel, respectively. In particular, if the individual decision of the generic user i^{th} is equal to H_0 then the user sends a flag representing 0 to the base station. On the contrary, if the individual decision is equal to H_1 then it sends a flag representing 1 to the base station. When the base station receives a flag, it makes a final decision according to a fusion rule. In particular, each SU sense the environment for a time equal to L and then makes the final decision at the end of the sensing phase. The base station or the master SU, collects the single decision and fuses it to make the final decision. The network deployment considered in this paper is based on the IEEE 802.22 wireless regional area network (WRAN) [14]. Local SUs monitor the presence of a PU (e.g., TV broadcast station) and send their detection as well as false alarm probabilities to the WRAN base station for combining them into one final decision. The cooperative sensing aims to improve the detection sensitivity at low SNR environments as well as to tackle the hidden terminal problem where the PUs activities might be shadowed from the local SU receiver by any existing intermediate obstacles [15-16]. Two fusion schemes are used in this paper, fusion OR- and AND- rule. In OR-rule fusion scheme, the final decision on the presence of a PU will be positive if only one SU of all cooperative users detects this PU. Assuming that all decisions are independent, the detection and false alarm probability of the secondary network under OR- rule can be written as:

$$P_d = 1 - \prod_{i=1}^M (1 - P_{d,i}) \quad (8)$$

$$P_f = 1 - \prod_{i=1}^M (1 - P_{f,i}) \quad (9)$$

where $P_{d,i}$, $P_{f,i}$ and M are the individual detection probability, false alarm probability and the number of cooperative SUs respectively. In case of all SUs have the same individual P_d and P_f , the joint probabilities of detection $Q_{d,OR}$ and false alarm $Q_{f,OR}$ can therefore be given as

$$Q_{d,OR} = 1 - (1 - P_d)^M \quad (10)$$

$$Q_{f,OR} = 1 - (1 - P_f)^M \quad (11)$$

In AND fusion scheme, all cooperative SUs should declare the presence of PUs in order to the final decision to be positive. Probabilities under AND rule can be represented as

$$P_d = \prod_{i=1}^M P_{d,i} \quad (12)$$

$$P_f = \prod_{i=1}^M P_{f,i} \quad (13)$$

In case of all SUs have the same individual P_d and P_f , joint probabilities of detection $Q_{d,AND}$ and false Alarm $Q_{f,AND}$ for M cooperating users using AND-rule can be calculated as

$$Q_{d,AND} = P_d^M \quad (14)$$

$$Q_{f,AND} = P_f^M \quad (15)$$

Now, we analyze the impact of the cooperative scheme on the average channel-search time T_s . Consider a conservative operation mode in which the channel is declared busy if only one cooperative user detects the PU (Logic OR fusion rule). Thus, the average channel-search time T_s can be expressed as follow:

$$T_s = \frac{L}{P_{idle}(1 - Q_f)} \quad (16)$$

where P_{idle} is the probability that the PU is inactive in the frequency band being sensed. Let, L_{min} is the minimum sensing time to obtain the maximum value of the probability of false alarm. Hence, the optimum sensing time (L^*) for each can be formulated as follows:

$$Q_f = 1 - (1 - P_f)^M \quad (17)$$

$$L^* = \arg \min \frac{L}{P_{idle}(1 - Q_f)} \quad (18)$$

$$P_d = 1 - (1 - Q_d)^{1/M} \quad (19)$$

$$L \geq L_{min}; N = L \times B \quad (20)$$

$$L_{min} = \frac{2}{B} \left(\frac{Q^{-1}(P_f) - Q^{-1}(P_d) \sqrt{1 + 2SNR}}{SNR} \right) \quad (21)$$

$$P_f = Q \left(SNR \times \sqrt{L \times (B/2)} + Q^{-1}(P_d) \sqrt{1 + 2SNR} \right) \quad (22)$$

In single stage spectrum sensing, the PU protection mode is realized by fixing the joint probability of detection as required level (Q_d). In cooperative spectrum sensing, the SU spectrum utilization mode is realized by fixing the joint probability of false alarm at the required level (Q_f).

$$P_d = Q\left(\frac{Q^{-1}(P_f) - SNR\sqrt{L \times (B/2)}}{\sqrt{1 + 2SNR}}\right) \quad (23)$$

4. Spectrum Utilization

In this section, we analyze the relationship between channel utilization and sensing duration for both local and cooperative sensing under the PU protection based transmission mode and SU spectrum utilization based transmission mode. In our system, each frame consists of one sensing slot (L) and one data transmission slot ($T-L$), where T is the total frame duration. Short sensing phase results in longer data transmission slot and higher throughput for SUs [17]. In the normal operation mode, the SU transmits its information, senses the environments periodically and makes a final decision about the state of the channel. When the SU declares the channel as busy, it must search another channel to continue its transmission. To analyze, we divide our channel utilization into two parts: one is in-band channel utilization where the channel is declared idle as well as sensing device is in normal operation mode and other is average channel utilization similar with that general scenario in which the channel can be declared idle or busy. Let the hypotheses H_0 and H_1 occur with probabilities $P(H_0)=P_{idle}$ and $P(H_1)=(1-P_{idle})=P_{busy}$, respectively. Then, during normal operation mode, sensing device decides for an idle channel in the following two cases:

1. Channel idle and declared idle equal to $(1-P_f) \times P_{idle}$ and
2. Channel busy and declared idle equal to $(1-P_d) \times P_{busy}$.

Let, $(T-L)/T$ is the percentage of time used for data transmission, then the in-band channel utilization can be defined as follow:

$$P_{ib} = \left[(1 - P_f) P_{idle} + (1 - P_d) P_{busy} \right] \times \left(\frac{T - L}{T} \right) \quad (24)$$

In average channel utilization, the SU must search a new idle channel only when it decides for the hypothesis H_1 . A channel is declared busy in two cases:

1. False alarm decision when channel is idle and declared busy equal to $P_f \times P_{idle}$.
2. Correct detection when channel is busy and declared busy equal to $P_d \times P_{busy}$.

In this case, the sensing device must cease all interfering transmission on the current channel, search a new idle channel and start again the transmission. The total time used by the sensing device to transmit, sense the channel, search a new channel and start new transmission is equal to $T_{tot}=(T+T_s+T_{move}+T_{set})$. Channel setup time ($T_{set}=2$ sec) is the window of time that may be taken by a wireless regional area network customer premises equipment (WRAN CPE) to transmit control information to a WRAN base station in order to establish operation with that base station at the prescribed power. Channel move up time ($T_{move}=2$ sec) is the time taken by a WRAN system to cease all interfering transmissions on the current TV channel upon detection of a licensed incumbent signal above the relevant incumbent detection threshold. Hence, the average channel utilization can be defined as follows

$$P_{avg} = [(P_f \times P_{idle}) + (P_d \times P_{busy})] \times \left(\frac{T-L}{T_{tot}} \right) \quad (25)$$

Using equations (24) and (25) we obtain total effective channel utilization for local sensing

$$P = P_{ib} + P_{avg} \quad (26)$$

In the PU protection scheme, we consider a target P_d to guarantee fixed protection of PU [18, 19]. In practice, the target P_d is chosen to be close to but less than 1. In IEEE 802.11 the requirements establish the minimum value of P_d equal to 0.9. SU utilization mode aims to standardize the spectrum utilization by SU. As such, probability of false alarm value P_f should be fixed as lower values (0.1) in order to guarantee fixed spectrum utilization for SUs. As seen in the local spectrum sensing, the channel utilization P depends on the probabilities that the WRAN decide for an idle or busy channel. In cooperative spectrum sensing, these two probabilities (in-band and average) can be expressed as follows

$$P_{ib} = [(1-Q_f) \times P_{idle} + (1-Q_d) \times P_{busy}] \times \left(\frac{T-L}{T} \right) \quad (27)$$

$$P_{avg} = [(Q_f \times P_{idle}) + (Q_d \times P_{busy})] \times \left(\frac{T-L}{T_{tot}} \right) \quad (28)$$

where Q_d and Q_f depend on particular fusion rule. Hence, using equation (27) and (28), the effective channel utilization of spectrum sensing using single stage sensing is given by

$$P = [(1-Q_f) \times P_{idle} + (1-Q_d) \times P_{busy}] \times \left(\frac{T-L}{T} \right) + [Q_f \times P_{idle} + Q_d \times P_{busy}] \times \left(\frac{T-L}{T_{tot}} \right) \quad (29)$$

In cooperative single stage spectrum sensing the PU protection scenario is realized by fixing the joint probability of detection ($Q_d=Q_d^*=0.9$) at the required level and minimizing the joint probability of false alarm Q_f as much as possible. Effective channel utilization can be expressed as

$$P = [(1-Q_f) \times P_{idle} + (1-Q_d^*) \times P_{busy}] \times \left(\frac{T-L}{T} \right) + [Q_f \times P_{idle} + Q_d^* \times P_{busy}] \times \left(\frac{T-L}{T_{tot}} \right) \quad (30)$$

where the joint probability of false alarm (Q_f) can be computed from the probability of false alarm of each user (P_f), the number of cooperative users and according to the fusion rule adopted. In cooperative single stage spectrum sensing, the SU spectrum utilization scenario is realized by fixing the joint probability of false alarm at the required level ($Q_f=Q_f^*=0.1$). The sensing time is chosen in order to obtain the minimum joint probability of detection Q_d defined in the requirements about sensing accuracy of IEEE 802.22 standard. Effective channel utilization for SU spectrum utilization scheme can be expressed as

$$P = [(1-Q_f^*) \times P_{idle} + (1-Q_d) \times P_{busy}] \times \left(\frac{T-L}{T} \right) + [Q_f^* \times P_{idle} + Q_d \times P_{busy}] \times \left(\frac{T-L}{T_{tot}} \right) \quad (31)$$

where the joint probability of detection can be computed from the probability of false alarm of each user, the number of cooperative users and according with the fusion rule adopted.

5. Performance Analysis

In this section, we present some numerical results to analyze the relationship between the spectrum utilization and the sensing time (L) for two different sensing schemes. We assume that the WRAN frame duration is 100 milliseconds (ms), SNR = -20.8 dB and $B = 6$ MHz throughout the analysis. Fig.1 shows the estimated P_f vs. L for different values of P_d achieved by the local sensing based PU protection mode. It can be observed from Fig.1 that at the same L , increasing P_d leads to increase the P_f and consequently, fewer chances for the SU to utilize the channel. It is also worth to observe that P_f decreases with increasing L .

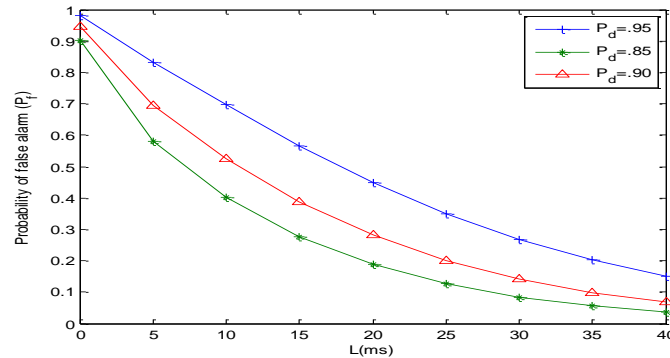


Figure 1. P_f vs. L at Different P_d

Figure 2 shows P_d as a function of L for different values of P_f achieved by the local sensing based SU spectrum utilization mode. It is clear from Figure 2 that increasing L leads to an improvement on the PU protection represented by increasing P_d . As we can see, at the same L , P_d decreases with decreasing P_f that leads to increase the spectrum usability. The effect of underutilization of channel P_{idle} on the local sensing based PU protection system is observed in Figure 3. Figure 3 depicts that effective channel utilization is highly dependent on L . From Figure 3, we find that there is an optimal sensing time (35 ms) at which the channel utilization is maximized. Moreover, Figure 3 reveals that the channel utilization increases if the underutilization of the channel P_{idle} is increased. In Figure 4, we plotted effective channel utilization achieved by the local sensing based SU spectrum utilization mode vs. L . Results show that channel utilization decreases with increasing L as well as increasing the protection level of the PU for different value of P_{idle} .

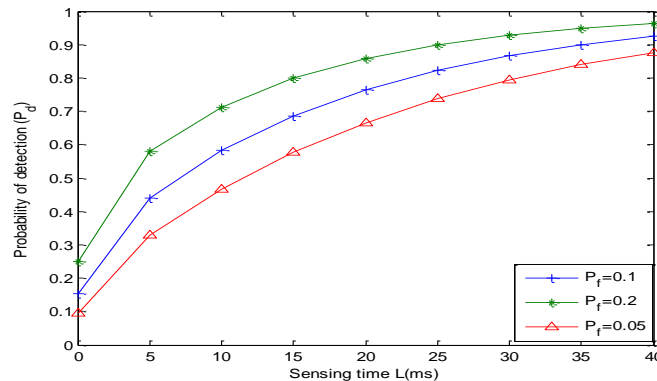


Figure 2. P_d vs. L at Different P_f

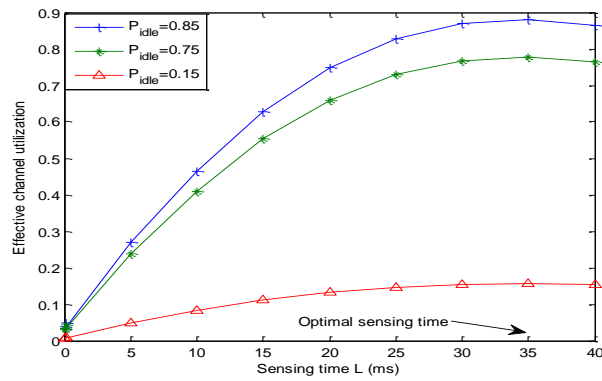


Figure 3. Effective Channel Utilization vs. L for Constant PU Protection Mode in Local Sensing

Again, since in this SU utilization scenario the probability of detection depend on the time used to sense the environment, we consider the maximum value allowed for the probability of false alarm, $P_f=0.1$. There is no optimal sensing time at which the SU capacity can be maximized. Now, we analyze the performance in cooperative spectrum sensing vs. effective channel utilization under PU protection and SU utilization mode. We consider performance analysis in the case of SUs grouped in clusters; hence all with the same average signal-to-noise ratio (SNR). In Figure 5 to Figure 9, we describe how the use of cooperative sensing schemes using hard fusion rule improves the performance of spectrum sensing. In Fig. 5 we plotted effective channel utilization achieved by the cooperative sensing based PU protection mode using logic OR fusion rule. Results show that effective channel utilization increases if the number of cooperative users is increased. This increased of performance is due to the behavior of the joint probability of false alarm Q_f that is plotted in the Figure 6. In Figure 6, we show that, the Q_f decreases if the sensing time L is increased. Moreover the figure also depicts that the joint probability of false alarm increases if the number of cooperative users is increased.

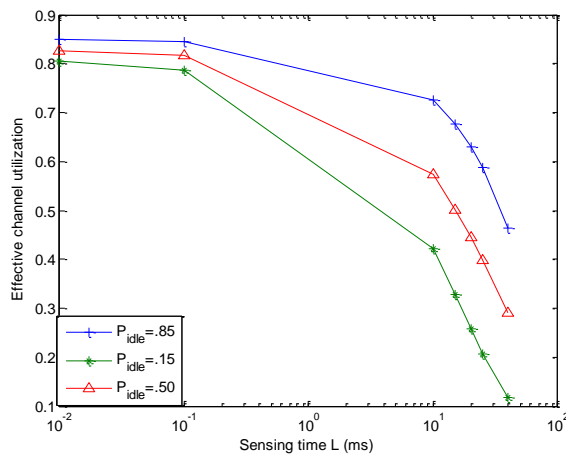


Figure 4. Effective Channel Utilization vs. L for SU Utilization Mode in Local Sensing

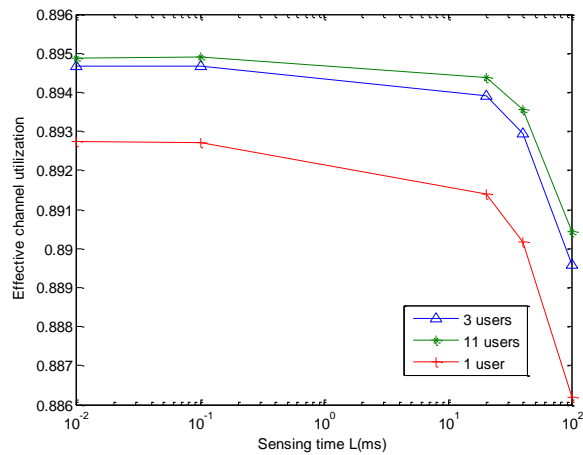


Figure 5. Effective Channel Utilization vs. L for PU Protection Mode in Cooperative Sensing (Logic OR Rule)

In Figure 7, we plotted effective channel utilization achieved by the cooperative sensing based secondary utilization mode using logic OR fusion rule. Results show that effective channel utilization increases with increasing the cooperative users in SU spectrum utilization mode. In Figure 8 we plotted effective channel utilization achieved by the logic AND fusion rule based cooperative sensing for primary user protection mode. From Figure 5 and 8 it is clear that logic OR fusion rule based cooperative sensing improves channel utilization for PU protection mode compared with logic AND fusion rule.

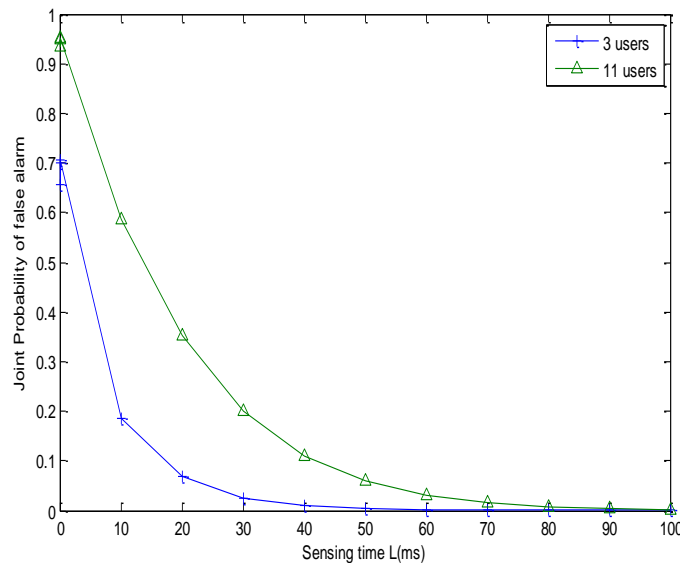


Figure 6. Joint Probability of False Alarm vs. L for PU Protection Mode in Cooperative Sensing (Logic OR Rule)

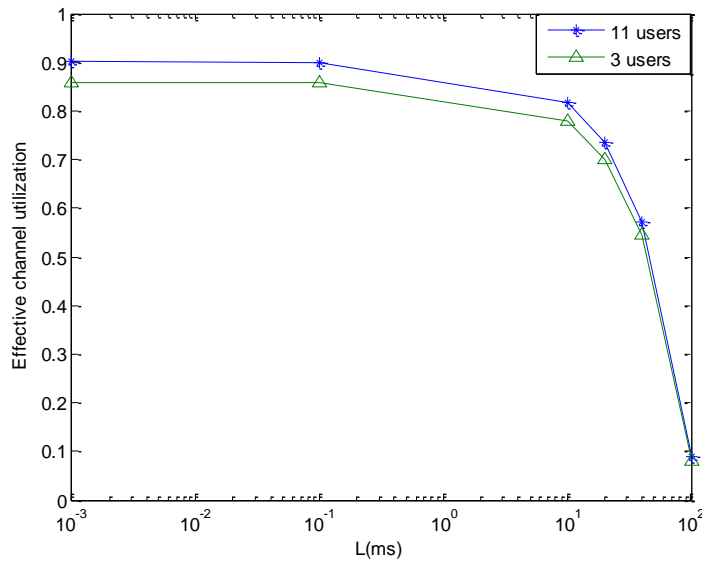


Figure 7. Effective Channel Utilization vs. L for SU Utilization Mode in Cooperative Sensing (Logic OR rule)

In Figure 9, we analyze the performance based on cooperative sensing using logic AND fusion rule. Figure 9 depicts that, effective channel utilization decreases if the sensing time is increased.

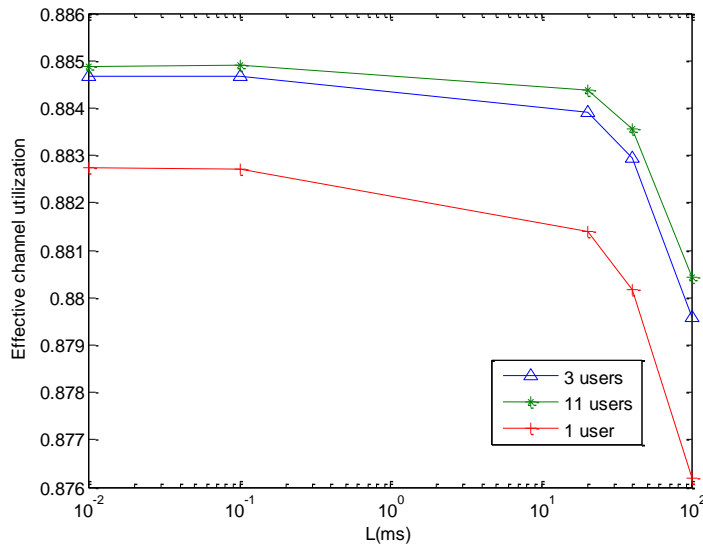


Figure 8. Effective Channel Utilization vs. L for PU Protection Mode in Cooperative Sensing (Logic AND Rule)

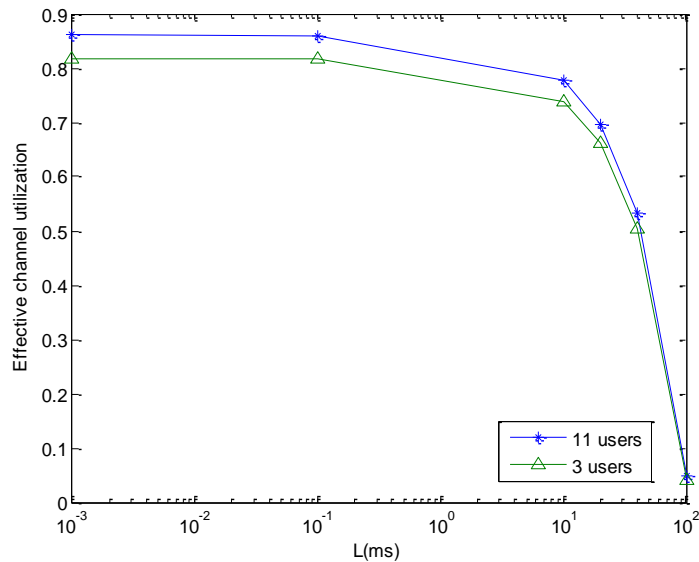


Figure 9. Effective Channel Utilization vs. L for SU Utilization Mode in Cooperative Sensing (Logic AND Rule)

It can be observed from Figure 7 and Figure 9 that logic OR fusion rule improves effective channel utilization for SU spectrum utilization mode compared with logic AND fusion rule. Our numerical analysis clearly shows that the cooperative sensing improves the performance of spectrum sensing.

6. Conclusion

Software defined radio or cognitive radio is an important component of the IEEE 802.22 standard being developed for Wireless Regional Area Network (WRAN) for operation in a license-exempt way over the TV broadcast bands [20]. In this paper, we describe and analyze the performance of WRAN system in both local and cooperative spectrum sensing. The performance is characterized through the effective channel utilization versus sensing time relationship for both local and cooperative spectrum sensing. The numerical results show that in local sensing under PU protection mode, the maximum effective channel utilization is achieved at an optimal sensing time. It was also found that increasing the protection level of PUs leads to increase the required optimal sensing time and reduces the channel utilization. In local sensing under SU spectrum utilization mode, it was observed that SU spectrum utilization continuously decreasing with increasing the sensing time and protection level of PUs. As expected, effective channel utilization increases in SU spectrum utilization mode as the number of cooperative users increase. The above analysis is useful in sensing phase design in CR medium access control design. Designing efficient and optimal sensing phase is a major concern for improving throughput in opportunistic spectrum access. Further research can be done by observing the effect of varying SNR values of PUs and total frame duration. However, to ensure efficient and optimal sensing phase in opportunistic spectrum access more research is needed along the lines introduced in this research.

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