

Capacity Optimization for Local and Cooperative Spectrum Sensing in Cognitive Radio Networks

Ayman A. El-Saleh, Mahamod Ismail, Mohd. A. M. Ali, and Ahmed N. H. Alnuaimy

Abstract—The dynamic spectrum allocation solutions such as cognitive radio networks have been proposed as a key technology to exploit the frequency segments that are spectrally underutilized. Cognitive radio users work as secondary users who need to constantly and rapidly sense the presence of primary users or licensees to utilize their frequency bands if they are inactive. Short sensing cycles should be run by the secondary users to achieve higher throughput rates as well as to provide low level of interference to the primary users by immediately vacating their channels once they have been detected. In this paper, the throughput-sensing time relationship in local and cooperative spectrum sensing has been investigated under two distinct scenarios, namely, constant primary user protection (CPUP) and constant secondary user spectrum usability (CSUSU) scenarios. The simulation results show that the design of sensing slot duration is very critical and depends on the number of cooperating users under CPUP scenario whereas under CSUSU, cooperating more users has no effect if the sensing time used exceeds 5% of the total frame duration.

Keywords—Capacity, cognitive radio, optimization, spectrum sensing.

I. INTRODUCTION

THE conventional fixed spectrum allocation, where the spectrum regulatory bodies give exclusive rights of radio resources to customers, has anxiously led to spectrum scarcity and inefficiency drawbacks. Recent measurements by Federal Communications Commission (FCC) show that 70% of the allocated spectrum in US is underutilized [1]. In addition, the fast-paced technologies and the extreme demands for new usable spectral segments call for innovative strategies to satisfy such a dilemma.

In 1999, there was a significant juncture in wireless communications when J. Mitola introduced his terrific idea of the cognitive radio (CR) as an upgraded version of the normal

software defined radio (SDR) armed with spectrum sensing capability over three degrees of freedom : time, frequency and space [2],[3]. The spectrum sensing is normally considered as a pure detection problem where the CR-assisted users have to scan a vast range of frequencies to observe available ‘white spaces’ or ‘holes’ that are temporarily and spatially available for transmission. The CR-assisted users are classified as secondary users (SUs) competing with primary users (PUs) who are obviously, Licensees, or alternatively, users of existing technologies on unlicensed bands (e.g. IEEE802.11a) [4]. The SUs are allowed to utilize the frequency bands of the PUs when they are not currently being used but they should willingly and quickly vacate the band once a PU has been detected. This fast vacation is necessary to avoid causing harmful interference to the PUs who should maintain ubiquitous and uninterrupted accessibility. Therefore, the SUs are required to periodically monitor the PUs activities using fast and reliable detection/sensing algorithms. In such algorithms, two probabilities are of interest: the first one is the probability of the sensing algorithm detecting the presence of a PU when it is active by discriminating its signal from noise, this is called the probability of detection, P_d . High detection probability is always required to ensure minimum level of interference to PUs. The other one is the probability of false alarm, P_f , which is defined as the probability of the sensing algorithm mistakenly detecting the presence of PUs while they are inactive. Low probability of false alarm should be targeted to offer more chances for SUs to use the sensed spectrum.

In this paper, the normalized capacity-sensing time relationship has been analyzed for local and cooperative sensing. In local sensing, a SU makes an individual decision on the presence of PUs, whereas in cooperative sensing, several SUs collaborate together to come out with a final decision on the presence of PUs by combining all individual decisions of local SUs at a central base station (BS) using OR or AND fusion schemes [5],[6]. The collaborative sensing is aimed 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 objects such as in fading environments [7]. In this work, the capacity of SU(s) of local and cooperative sensing is analyzed under two operational modes, namely, the constant primary user protection (CPUP) and constant secondary user spectrum usability (CSUSU) scenarios. In CPUP scenario, the interference from SUs to PUs will be set to a specific level that is low enough to ensure

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ubiquitous and uninterrupted service for the active PUs. This is done by fixing the probability of detecting PUs to a high value, e.g. $P_d = 0.9$, while minimizing the probability of false alarm. On the other hand, in CSUSU scenario, the usability of unoccupied bands by SUs can be kept constant by setting the probability of false alarm at a certain level, e.g. $P_f = 0.1$, while maximizing the probability of detection. In this paper, the capacity of the SU network is analyzed under these two operational modes. This paper is organized as follows: Section II reviews the channel sensing hypotheses, energy detector, and the CPUP and CSUSU transmission modes for local spectrum sensing. In section III, the cooperative spectrum sensing is presented using OR and AND fusion schemes. The performance of local and cooperative spectrum sensing is characterized in section IV, and finally, the conclusions are drawn in section V.

II. LOCAL SPECTRUM SENSING

In local sensing, each SU senses the spectrum within its geographical location and makes a decision on the presence of primary user(s) based on its own local sensing measurements.

A. Channel Sensing Hypotheses

Consider a SU in a cognitive radio system sensing a frequency band W and a received demodulated signal is sampled at sampling rate, f_s , then $f_s \geq W$. Hence, the sampled received signal, $X[n]$ at the SU receiver will have two hypotheses as follows:

$$\begin{aligned} \mathcal{H}_0: X[n] &= W[n] & \text{if PU is absent} \\ \mathcal{H}_1: X[n] &= W[n] + S[n] & \text{if PU is present} \end{aligned} \quad (1)$$

where $n = 1, \dots, K$; K is the number of samples. The noise $W[n]$ is assumed to be additive white Gaussian (AWGN) with zero mean and variance σ_w^2 . $S[n]$ is the primary user's signal and is assumed to be a random Gaussian process with zero mean and variance σ_s^2 . The goal of the local spectrum sensing is to reliably decide on the two hypotheses with high probability of detection, P_d , and low probability of false alarm, P_f . P_d and P_f can now be defined as the probabilities that the sensing SU algorithm detects a PU under \mathcal{H}_0 and \mathcal{H}_1 , respectively.

B. Statistical Model of Energy Detector

The energy detector is known as a suboptimal detector, which can be applied to detect unknown signals as it does not require a prior knowledge on the transmitted waveform as the optimal detector (matched filter) does. The decision statistic, T , for energy detector is given by

$$T = \sum_{n=1}^K (X[n])^2 \quad (2)$$

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

$$\begin{aligned} P_f &= P(T > \beta | \mathcal{H}_0) \\ P_d &= P(T > \beta | \mathcal{H}_1) \end{aligned} \quad (3)$$

where β is a particular threshold that tests the decision statistic. Since we are interested in low signal-to-noise ratio of primary user ($SNR_p = \sigma_s^2 / \sigma_w^2$) regime, large number of samples should be used. Thus, the test statistic chi-square distribution can be approximated as Gaussian based on the central limit theorem. Then

$$P_f = Q\left(\frac{\beta - K\sigma_w^2}{\sqrt{2K\sigma_w^4}}\right) \quad (4)$$

$$P_d = Q\left(\frac{\beta - K(\sigma_w^2 + \sigma_s^2)}{\sqrt{2K(\sigma_w^2 + \sigma_s^2)^2}}\right) \quad (5)$$

C. Cognitive Radio Transmission Scenarios

1) Constant Primary User Protection (CPUP) Scenario:

This transmission mode is viewed from the PUs' perspective. It guarantees a minimum level of interference to PUs who by right, should not be affected by the SUs transmission. This scenario can be realized by fixing P_d at a satisfactory level, e.g. 90%, and trying to minimize P_f as much as possible. Thus, P_f is derived to be

$$P_f = Q\left(Q^{-1}(\bar{P}_d)(1 + SNR_p) + SNR_p \sqrt{\frac{K}{2}}\right) \quad (6)$$

where the number of samples, K , is the product of sensing time times sampling frequency. Fig. 1 shows the estimated P_f versus sensing time (t_s) at different protection levels. The SNR_p is set to -18 dB throughout the local sensing simulations. It is clear that P_f can be minimized by increasing the sensing time. However, at the same sensing time, increasing the PUs protection level by stating higher P_d values leads to increase P_f and consequently, fewer chances for SUs to utilize the spectrum. Therefore, there will be a tradeoff between these two conflicting objectives.

2) Constant Secondary User Spectrum Utilization (CSUSU) Scenario

This mode is taken from the SUs' perspective; it aims to standardize the spectrum utilization by SUs. As such, the P_f values should be fixed at lower values (e.g. $\leq 10\%$) while keep maximizing P_d which can be written in terms of a desired P_f as follows

$$P_d = Q \left(\frac{Q^{-1}(\bar{P}_f) - \sqrt{\frac{K}{2}} SNR_p}{1 + SNR_p} \right) \quad (7)$$

Fig. 2 shows that increasing the sensing time leads to an improvement on the PU protection represented by increasing P_d . However, at the same sensing time, increasing the spectrum usability by decreasing P_f leads to decrease P_d that is the protection of PUs. Again, these two objectives conflict each other.

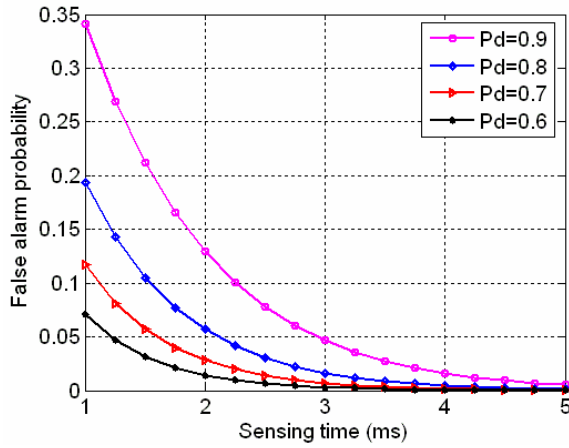


Fig. 1 False alarm probability versus sensing time at different detection probabilities

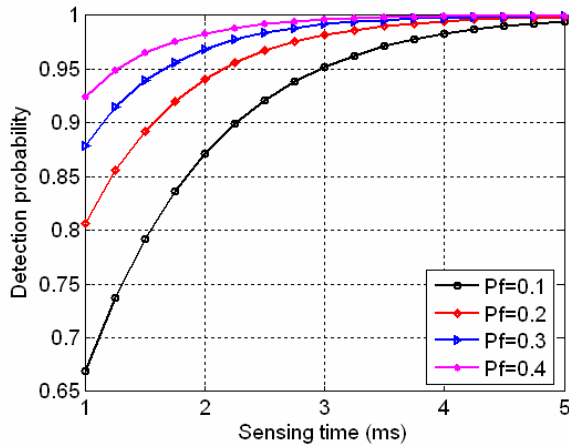


Fig. 2 Detection probability versus sensing time at different False alarm probabilities

III. COOPERATIVE SPECTRUM SENSING

The collaborative 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. This section presents the SU cognitive radio network model using some well-known fusion schemes. In addition, the overall network PU detection and false alarm probabilities will be derived for the CPUP and CSUSU transmission scenarios, respectively.

A. Cognitive Radio Network Deployment

The network deployment in this paper is based on the IEEE 802.22 WRAN [5]. The WRAN base BS collects information on the PU activities from the SUs within its coverage area as shown in Fig. 3. Local SUs keep monitoring the presence of a PU, which is a TV broadcast station, and send their detection and false alarm probabilities to the base station for combining them into one overall final decision. In this scenario, it is assumed that the TV BS is far away from the WRAN BS and therefore, low SNR_p values are used.

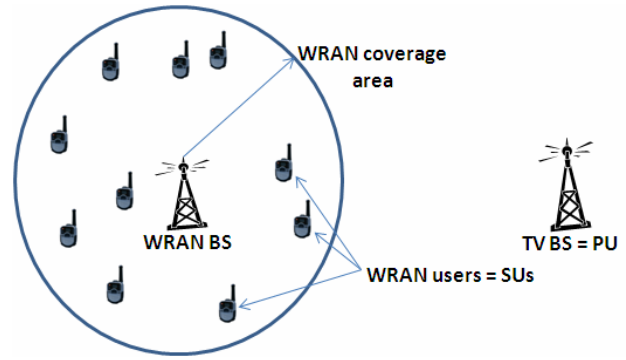


Fig. 3 A simplified representation of an IEEE 802.22 WRAN system deployment

B. Fusion Schemes for Local Secondary Users' Decisions

At the SUs base station, all local sensing information are combined and merged into one final decision using Chair-Varshney fusion schemes [6],[7]. Two fusion schemes are used in this paper, 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 collaborating users detects this PU. Assuming that all decisions are independent, the detection and false alarm probability of the SUs network under OR-rule, P_d and P_f , respectively, can then be mathematically written as

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

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

where $P_{d,i}$ and $P_{f,i}$ are the individual detection probability and false alarm probability, respectively. N is the number of cooperating SUs. In AND-rule fusion scheme, all

collaborating SUs should declare the presence of a PU in order for the final decision to be positive. Again, assuming that all decisions are independent, the SUs network probabilities under AND-rule can be presented as

$$P_d = \prod_{i=1}^N P_{d,i} \quad (10)$$

$$P_f = \prod_{i=1}^N P_{f,i} \quad (11)$$

C. Estimation of Network Probabilities under CPUP and CSUSU Scenarios

In this section, the SUs network false alarm and detection probability formulas have been derived under CPUP and CSUSU scenarios, respectively. To ease the understanding of network probabilities derivations, Table I is introduced. It presents the substitution sequence of equations (6) to (11) to derive the four combinations of transmission mode-fusion scheme. Let's here take the CPUP transmission mode using OR fusion scheme as an example and apply the corresponding substitution sequence in the table to derive the false alarm probability of the SUs network, P_f . firstly, we find the individual desired detection probability, $\bar{P}_{d,i}$, in terms of the desired network detection probability, \bar{P}_d , using (8). Secondly, the probability of false alarm of each SU, $P_{f,i}$, can be found by substituting the $\bar{P}_{d,i}$ equation into (6). Finally, P_f is estimated by substituting the $P_{f,i}$ equation into (9). Thus, P_f for CPUP-OR combination is

$$P_f = 1 - \prod_{i=1}^N \left(1 - Q \left(\frac{Q^{-1} \left(1 - (1 - \bar{P}_d)^{\frac{1}{N}} \right) \times \dots}{(1 + SNR_{p,i}) + SNR_{p,i} \sqrt{\frac{K}{2}}} \right) \right) \quad (12)$$

Similarly, P_f for CPUP-AND combination can be derived as

$$P_f = \prod_{i=1}^N Q \left(Q^{-1} \left((\bar{P}_d)^{\frac{1}{N}} \right) (1 + SNR_{p,i}) + SNR_{p,i} \sqrt{\frac{K}{2}} \right) \quad (13)$$

In CSUSU scenario, the false alarm probability of the SUs network is set constant at \bar{P}_f , and the detection probability of the SUs network, P_d , is calculated accordingly using the substitution sequence in table I. Thus, for CSUSU-OR

$$P_d = 1 - \prod_{i=1}^N \left(1 - Q \left(\frac{Q^{-1} \left(1 - (1 - \bar{P}_f)^{\frac{1}{N}} \right) - \sqrt{\frac{K}{2}} SNR_{p,i}}{(1 + SNR_{p,i})} \right) \right) \quad (14)$$

Similarly, for CSUSU-AND

$$P_d = \prod_{i=1}^N Q \left(\frac{Q^{-1} \left((\bar{P}_f)^{\frac{1}{N}} \right) - \sqrt{\frac{K}{2}} SNR_{p,i}}{(1 + SNR_{p,i})} \right) \quad (15)$$

TABLE I
DERIVATION FLOW OF SUs TRANSMISSION MODES USING OR AND FUSION SCHEMES

Transmission mode-fusion scheme	Derivation flow
CPUP-OR	(8) → (6) → (9)
CPUP-AND	(10) → (6) → (11)
CSUSU-OR	(9) → (7) → (8)
CSUSU-AND	(11) → (7) → (10)

IV. CAPACITY OPTIMIZATION FOR LOCAL AND COOPERATIVE SPECTRUM SENSING

In this section, we analyze the relationship between SUs capacity and sensing capability for both local and cooperative sensing under the CPUP and CSUSU transmission modes. In WRAN system, each frame consists of one sensing slot (t_s) plus one data transmission slot ($T_f - t_s$), where T_f is the total frame duration. Indeed, short sensing slots should be always aimed as it results in longer data transmission slot and therefore, higher throughput capacity.

A. Problem Formulation

There are two cases for which the SUs network might operate at the PU's licensed band: first when the PU is inactive and the SUs successfully declare that there is no PU. In this case, the normalized capacity of the WRAN system is represented as

$$C_0 = \left(1 - \frac{t_s}{T_f} \right) (1 - P_f) P(\mathcal{H}_0) \quad (16)$$

where $P(\mathcal{H}_0)$ is the probability that the PU is inactive in the frequency band being sensed. The other case is when the PU is active but the SUs fail to detect it. The normalized capacity is then given by

$$C_1 = \left(1 - \frac{t_s}{T_f} \right) (1 - P_d) P(\mathcal{H}_1) \quad (17)$$

where $P(\mathcal{H}_1)$ is the probability of the PU being active in the frequency band of interest. Obviously, $P(\mathcal{H}_0) + P(\mathcal{H}_1) = 1$. The objective of this research is to determine the optimal sensing time for each frame such that the SUs network capacity is

maximized. Consequently, this objective can be formed as an optimization problem described as follows:

$$\max C = \left(1 - \frac{t_s}{T_f}\right) [(1 - P_f) P(\mathcal{H}_0) + (1 - P_d) P(\mathcal{H}_1)]$$

Subject to: $0 < t_s \leq T_f$ and

$$P_d \geq \bar{P}_d \text{ under CPUP or } P_f \leq \bar{P}_f \text{ under}$$

CSUSU

(18)

B. Capacity Optimization for Local Spectrum Sensing

In this section, MATLAB simulations have been performed to analyze the capacity-sensing capability relationship. The WRAN frame duration was set to 100 ms and the one-side bandwidth of PU bandpass signal is selected to be 3MHz. The SNR_p is set to -18 dB. For local spectrum sensing under CPUP transmission scenario, the simulation results show that though P_f decreases with increasing the sensing time as was shown in Fig. 1, however, Fig. 4 shows that decreasing P_f does not lead to an absolute increase in the SU throughput as thought but instead, there is an optimal sensing time at which the throughput is maximized. Fig. 4 also reveals that this optimal sensing time increases by increasing the fixed P_d .

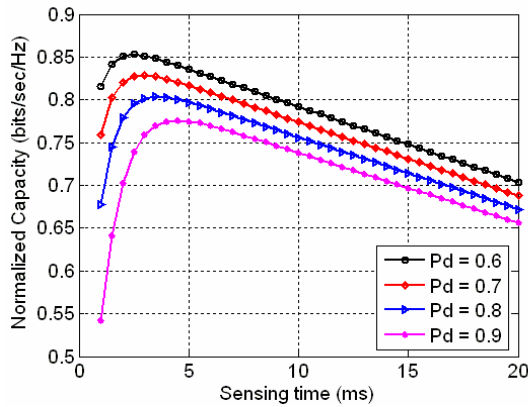


Fig. 4 Normalized capacity versus sensing time at different detection probabilities under CPUP transmission mode

In Fig. 5, It is worth to observe that this optimization tradeoff exists only at low SNR_p values whereas at high SNR_p values, the capacity-sensing time relation becomes decremental for any $t_s < T_f$. The simulation results for the SNR_p effect have been performed to prove this finding. Under CSUSU scenario, Fig. 2 depicted that P_d increases with increasing the sensing time, this means that the PU will be more protected but unfortunately, the SU capacity will be decreased as shown in Fig. 6. Fig. 6 also shows that the SU capacity degrades with increasing P_f . In contrast to CPUP

case, Fig. 7 shows that the SU capacity under CSUSU mode is higher for lower SNR_p values when short sensing time is used whereas at longer sensing times, the SU capacity becomes linear and independent of SNR_p .

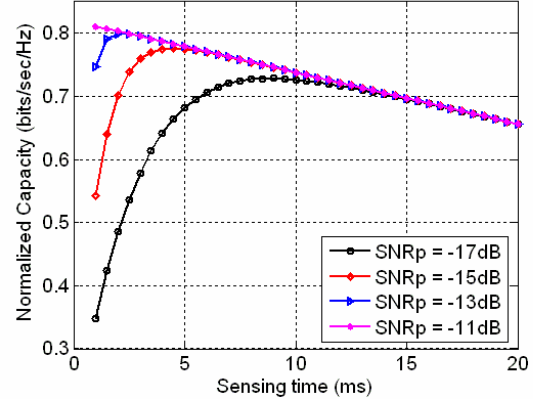


Fig. 5 Normalized capacity versus sensing time at different PU SNR values under CPUP transmission mode

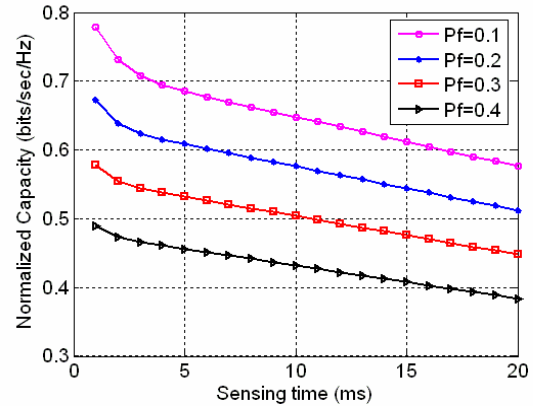


Fig. 6 Normalized capacity versus sensing time at different false alarm probabilities under CSUSU transmission mode

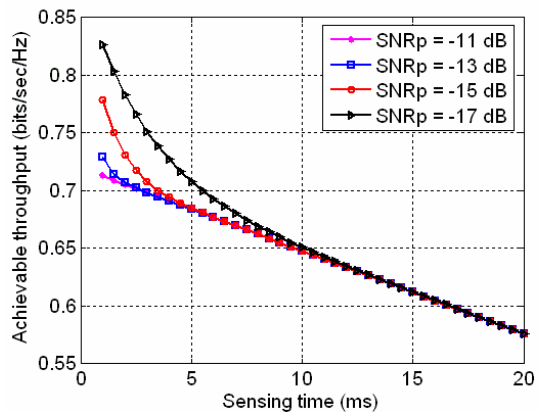


Fig. 7 Normalized capacity versus sensing time at different PU SNR values under CSUSU transmission mode

C. Capacity Optimization for Cooperative Spectrum Sensing

In cooperative sensing, all WRAN users in the coverage area of the WRAN BS will perform individual repetitive sensing cycles and send their individual decisions to the WRAN BS as individual detection and false alarm probabilities. The sensing time period which is a fraction of total frame time transmitted by the SU network should be as minimal as possible to maximize the SU network capacity. In order to estimate the capacity of WRAN network under, let say, CPUP scenario, we should first determine the overall P_f of the network using (12) or (13) for OR or AND fusion schemes, respectively. Then, the estimated P_f together with the desired fixed P_d are substituted in (18) to calculate the overall capacity of the network. Similar procedure applies for CSUSU scenario. In this section, the number of cooperating SUs, N , is varied from 1 user (no cooperation) to 20 users (all available users in the network are cooperating). The optimal sensing time is defined as the sensing time duration at which the SUs network capacity is maximized. First, consider the CPUP mode, Fig. 8 shows that the maximum SUs network capacity increases by cooperating more users in the network using OR and AND fusion schemes. The corresponding optimal sensing time required to achieve the maximum capacity for various number of users is evaluated in Fig. 9. Fig. 9 reveals that cooperating more users will reduce the optimal sensing time required to achieve the maximum throughput. Thus, the good detection algorithm should consider the local measurements of all available cognitive SUs in the network. This will interestingly reduce the optimal sensing time and improve the SU network capacity. Under CSUSU mode, using either OR or AND fusion scheme, and as pictured in Figs. 10 and 11, respectively, it was found that at short sensing times, e.g. t_s is less than 5% of total frame duration, cooperating more users reduces the network capacity whereas at longer sensing times, there was no effect on the network capacity by increasing the number of cooperating users in the network.

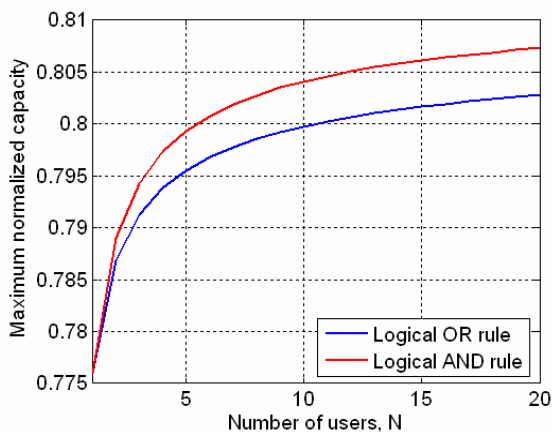


Fig. 8 Maximum normalized capacity versus number of users under CPUP mode using logical OR and OR fusion schemes

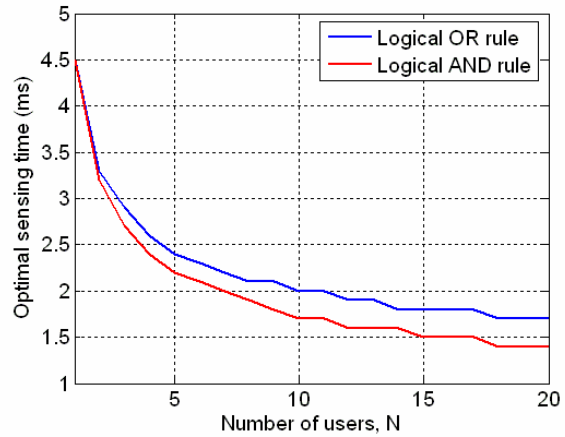


Fig. 9 Optimal sensing time versus number of users under CPUP mode using logical OR and OR fusion schemes

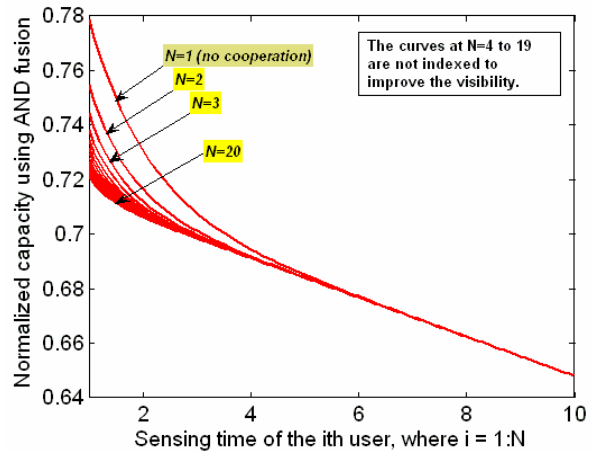


Fig. 10 Normalized capacity versus sensing time for N users under CSUSU mode using logical AND fusion scheme

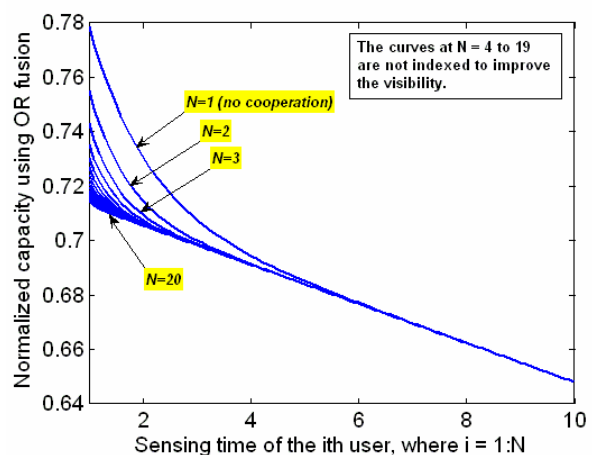


Fig. 11 Normalized capacity versus sensing time for N users under CSUSU mode using logical OR fusion scheme

V. CONCLUSION

In this paper, The WRAN system performance has been investigated using two operational modes, namely, CPUP and CSUSU. The performance is characterized through the normalized capacity versus sensing time relationship for both local and cooperative sensing. The simulation results show that in local sensing under CPUP transmission mode, the maximum SUs capacity is achieved at a unique 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 achievable maximum capacity. In cooperative sensing under CPUP as well, the performance of SUs network can be improved by cooperating more users in the network. In local sensing under CSUSU mode, it was observed that there is no optimal sensing time at which the SU capacity can be maximized. The SU capacity continuously decreases with increasing the sensing time as well as increasing the protection level of PUs. In cooperative sensing, it was found that cooperating more users in the network has no effect if the sensing slot exceeds 5% of the total frame duration. In this research, some parameters were assumed to be constants such as the SNR values of PUs and total frame duration. Further research can be done by observing the effect of varying such parameters in the overall performance of SUs network.

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