Performance Analysis of Throughput Maximization Techniques in Cognitive Radio using Cooperative Spectrum Sensing

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Abstract: Many research activities are undergoing nowadays in the field of cognitive radio (CR). Throughput maximization is one of the major issues in CR to enhance the performance of the system. Throughput in CR can be enhanced by selecting the appropriate sensing time and appropriate number of users involved in the spectrum sensing. Besides these two factors, designing appropriate fusion rule at the fusion centre of the CR network is another issue. In this study, three throughput maximization techniques are analyzed viz. adjustment of number of users, selection of appropriate sensing time and selection of appropriate fusion rule. Knowing the fact that cooperation enhances the performance of CR network, cooperative spectrum sensing is used in all these techniques. Energy detection method is used for spectrum sensing, where characteristics of primary user signal is unnecessary for secondary users to decide upon the availability of vacant bands but only requirement is to identify the presence or absence of the primary user signal based on the power. Time division combining cooperative spectrum sensing (TDC-CSS) is used for the fusion rule at the fusion centre. To show the relationship of throughput with above parameters, a simulation is set up and the optimum values are found. The simulation results show that throughput in CR network can be maximized by decreasing the number of users, not allocating much sensing time and using majority decision combining at the fusion centre. For the simulated CR system, sensing time of 25 ms and 2 number of CR users is found to be appropriate. Also using TDC-CSS, the maximum throughput of the system is found to be increased by 32% with sensing time allocation of 5 ms only.

Keywords: spectrum sensing; throughput; energy detection; cooperation; primary user; secondary user

1. Introduction

The usable electromagnetic radio spectrum is a precious natural resource but it is of limited physical extent [1]. Cognitive radio (CR) network addresses the spectrum scarcity problem by allowing unlicensed users (secondary users, SUs) to access licensed spectrum on the condition of not disrupting the communication of licensed users (primary users, PUs). For this, SUs sense the licensed channels to detect the PU activities and find the underutilized “white spaces”, the process is known as spectrum sensing [2].

In cooperative spectrum sensing (CSS), individual CR users sense the channel and send their sensing information to the network centre (also called fusion centre), where the final decision is made. For spectrum sensing, energy detection (ED) method is used, which does not require the characteristics of the primary signals; only presence or absence of the signal is enough to make decision [3].

Throughput in a system can be defined as the number of successful data delivered over a communication channel. This data may be delivered over a physical or logical link or pass through certain network node. The throughput is usually measured in bits per second (bits/s or bps). Maximization of the throughput is the major challenge of any communication system because throughput represents the overall performance of the system. In CR network, there are three approaches of maximization of throughput, these are: using optimum number of SUs involved in spectrum sensing, allocating appropriate time duration for spectrum sensing and using appropriate fusion rule at the fusion centre.

There are three parameters related to spectrum sensing: detection probability (p_d), false alarm probability (p_f) and miss probability (p_m). Detection probability is the probability of detecting the PU by SU when PU is present in the channel. False alarm probability is the probability that SU detects PU in the spectrum when PU is actually not present. Miss detection probability is the probability that SU does not detect PU in the spectrum when PU is actually present there. Detection can be improved if the spectrum sensing time taken by the SU is increased but this increase in sensing time decreases the throughput of the system because in a detection cycle, SU first senses the spectrum and transmits data. If sensing time is made larger, data transmission time decreases which degrades the throughput. So, there exists a tradeoff between the sensing time and the throughput in the CR network [4].

2. Related Works

Several researches are being done in the field of cognitive radio. Throughput maximization is one of the major challenges in CR network. Regarding throughput maximization techniques, different researches are being done but many techniques are based on either selecting optimal number of SUs or the optimal sensing duration. Besides these two, optimal combining at the fusion centre is another research interest, where throughput maximization is done by dividing the sensing time so that the reporting time i.e. the time required for one SU to send the decision to fusion centre can be utilized by the second SU to sense the spectrum.

Different combining scheme and their effect on throughput was studied in [2]. They derived advanced combining scheme in the fusion centre based on Bayesian decision rule that provided better throughput as compared to AND, OR and MAJORITY decision rule.

ED based CSS was used to enhance the throughput of the system in [3]. The throughput was improved in terms of fusion rule. K out of N rule was used in the fusion centre and novel process of CSS was proposed [3].

The concept of sensing throughput tradeoff was given in [5] where, the throughput of the CR network was maximized under the constraint of predefined detection probability (p_d). Both cooperative and non cooperative spectrum sensing were studied by them and concluded that cooperative spectrum sensing gives better throughput performance. For cooperative spectrum sensing, K out of N rule, which is a majority decision rule, was used.

The results of [5] was modified by [6] for low signal to noise ratio (SNR) condition. They concluded that allocating longer time for spectrum sensing enhances spectrum sensing but does not enhance throughput. Up to small time of sensing, the throughput increased slowly with sensing time but as the sensing time further increased, the throughput of the system decreased rapidly.

Iterative algorithm was proposed in [7], where, optimum number of users in CR network for predefined number of iterations was found. Throughput was found to be maximum for small number of SUs involved in cooperation.

Yu, Tang, and Li (2011) maximized the throughput of the system using energy detection based cooperative spectrum sensing. In the fusion centre, they used weighted summation method of decision. The weighted sum of decision from different SUs was calculated at the fusion centre and final decision was made by comparing the result with the threshold. Additive white Gaussian noise (AWGN) and Rayleigh channel model were used as fading environment. They considered that cooperation enhances throughput but their result showed that increasing the number of SUs does not necessarily improve the throughput. Up to certain number of SUs, the throughput increased but upon further increasing the number of SUs, throughput started to decrease [8].

Improvement of throughput was done in [4] by combining the result from [6] and [8]. According to them, throughput can be enhanced either by optimizing sensing time or optimizing the number of SUs involved in cooperation. But they did not mention the number of secondary users for which the throughput of the system is maximum.

Hu, Li, Wu, Xu, and Chen (2012) proposed time domain combining cooperative -spectrum sensing (TDC-CSS) in which they improved throughput compared to classical CSS. In this scheme, they used the concept that the time required for reporting the decision by one SU can be utilized by another SU to sense the spectrum [9].

Liang, Zeng, Peh, and Hoang (2008) proposed that there exists a tradeoff between the sensing time and throughput in a CR network. Their graphical results show that upon increasing the detection probability, throughput of the system decreases and upon decreasing the detection probability, throughput of the system increases [10].

The main task of our work is to maximize the throughput in terms of sensing time and number of SUs as in [4] along with the effect of optimal combining scheme using TDC-CSS in the fusion centre.

3. System Model

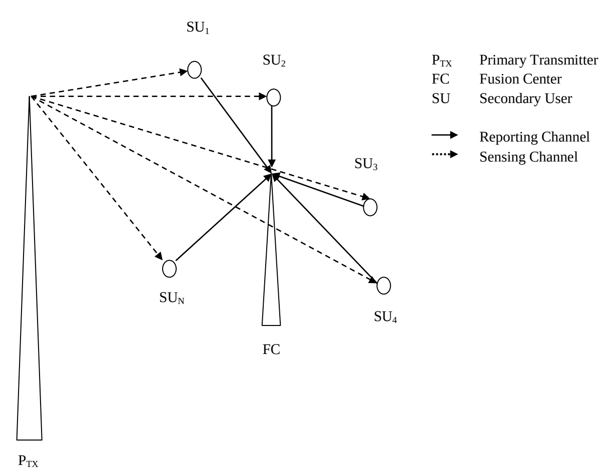

Figure 1: System model

Let us consider a CR network consisting of a primary transmitter (P_{TX}) and M number of secondary users as shown in Figure 1. There are separate channels for reporting and sensing. Reporting channel is used to send the sensing information by each SU to the fusion centre. Sensing channel is used to detect the presence or absence of PU in the channel i.e. for spectrum sensing. Let N out of M SUs are only involved in cooperation.

It is assumed that the distance between the CR users is small compared to the distance between PU and CR users. Then the path loss of each CR users are considered to be independent and identically distributed (IID).

Reporting channel is not perfect channel so that there may be some errors in the decision bits which are transmitted by SU to the fusion centre. Let θ denote the reporting error between the CR user and the fusion centre, ζ denote the local decision bit and D denote the bit received by fusion centre from the CR user. Then:

$$\begin{aligned} p\left\{D=0\middle|\zeta=1\right\} &= p\left\{D=1\middle|\zeta=0\right\}=\theta, \\ p\left\{D=0\middle|\zeta=0\right\} &= p\left\{D=1\middle|\zeta=1\right\}=1-\theta. \end{aligned} \quad \text{..........(1)}$$

Equivalent false alarm and detection probability are given as [9]:

$$\begin{aligned} \hat{p}_f &= p_f(1-\theta)+(1-p_f)\theta, \\ \hat{p}_d &= p_d(1-\theta)+(1-p_d)\theta. \end{aligned} \quad \text{..........(2)}$$

3.1 *Frame Structure*

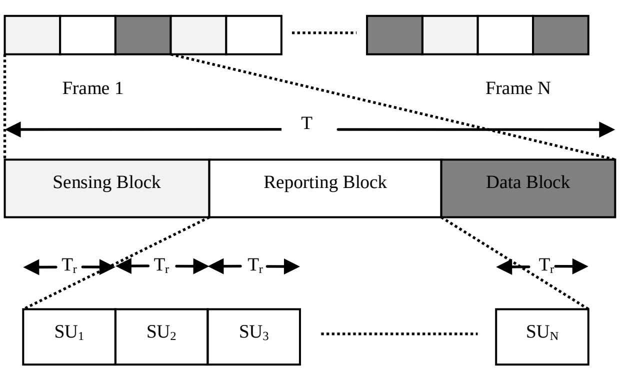

Figure 2: Frame structure for cognitive radio network

The frame structure for cooperative spectrum sensing has been illustrated in Figure 2. Here, each frame consists of three parts: a sensing block, a reporting block and a data transmission block. Suppose that frame duration is T, sensing duration is T_s and individual reporting duration is T_r. In the sensing block, all the SUs conduct spectrum sensing simultaneously. In the reporting block, the local sensing results are reported to the fusion centre sequentially via the common control channel. Then, the fusion centre makes the final decision to indicate absence or presence of the primary user [8] [9].

3.2 *Energy Detection*

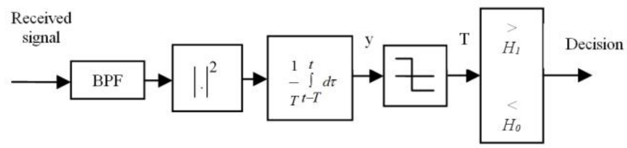

Figure 3: Block diagram of energy detector

Let us consider that $y_i(n)$ be the received signal at i^{th} SU, where i =1, 2, 3..N. Then, $y_i(n)$ can be represented as:

$$y_i(n)=\begin{cases} w_i(n)\text{....................}H_0,\ n=1,2,3,...,T_s f_s \\ h_i x_i(n)+w_i(n)\text{..}H_1,\ n=1,2,3,...,T_s f_s \end{cases} \text{..(3)}$$

Here, H_0 and H_1 represent the formula for binary hypothesis that the PU is absent or present in the channel respectively, h_i denotes the channel coefficient from the PU to the i^{th} SU and $w_i(n)$ represents the Gaussian noise with mean 0 and variance σ_w^2.

The received signal at each SU is sampled at sampling frequency (f_s). The test statistic $T(y_i)$ can be given according to above figure 3 as:

$$T(y_i)=\frac{1}{T_s f_s}\sum_{n=1}^{T_s f_s}\left|y_i(n)\right|^2, \quad \text{..........(4)}$$

where, $T(y_i)$ follows Gaussian distribution and is given as:

$$T(y_i)\sim\begin{cases} N(\sigma_w^2,\frac{1}{T_s f_s}\sigma_w^4)\text{......................................}H_0 \\ N(\sigma_w^2(1+\gamma_i),\frac{1}{T_s f_s}\sigma_w^4(1+2\gamma_i))\text{....}H_1. \end{cases} \text{...(5)}$$

Here, $\gamma_i=\frac{\left|h_i\right|^2\sigma_s^2}{\sigma_w^2}$ represents the instantaneous SNR at the i^{th} SU and σ_s^2 represents the signal power.

Hence according to [7], probability of false alarm $p_f=p(T(y_i>\lambda\left|H_0\right.))$, probability of detection

$p_d = p(T(y_i > \lambda | H_1))$ and miss detection probability $p_m = p(T(y_i < \lambda | H_1))$ are given as:

$$p_f = \frac{1}{2}\operatorname{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{\lambda}{\sigma_w^2} - 1\right)\sqrt{T_s f_s}\right), \qquad \text{..........(6)}$$

$$p_d = \frac{1}{2}\operatorname{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{\lambda}{\sigma_w^2} - \gamma - 1\right)\sqrt{\frac{T_s f_s}{2\gamma + 1}}\right), \text{.........(7)}$$

$$p_m = 1 - p_d. \qquad \text{..........(8)}$$

Here, λ is the decision threshold given as:

$$\lambda = \sigma_w^2 \left\{ \frac{\left(\sqrt{2(2\gamma+1)}\operatorname{erfcinv}(2.p_{th}) + \gamma\sqrt{T_s f_s}\right)}{\sqrt{T_s f_s}} + 1 \right\}, \text{(9)}$$

where, p_{th} is the minimum requirement of p_d. Now, overall false alarm probability (Q_f), the overall detection probability (Q_d) and overall miss detection probability (Q_m) in cooperative spectrum sensing is given as:

$$Q_f = 1 - \left(1 - p_f\right)^N, \qquad \text{.......(10)}$$

$$Q_d = 1 - \left(1 - p_d\right)^N, \qquad \text{.......(11)}$$

$$Q_m = \left(p_m\right)^N. \qquad \text{.......(12)}$$

3.3 Optimum Number of CR Users and Sensing Time

A SU in CR network can transmit data when PU is not active i.e. the decision goes in favor of false alarm or missed detection. The overall throughput in these two cases is given as:

$$R = \frac{T - T_s - NT_r}{T} p(H_0)(1 - Q_f)C_0 + \frac{T - T_s - NT_r}{T} p(H_1)(1 - Q_d)C_1, \qquad \text{.......(13)}$$

where, C_0 and C_1 denote the throughput of CR network if operated in absence and presence of PU respectively, $p(H_0)$ and $p(H_1)$ are probabilities that the PU is absent and present respectively.

Thus, maximum throughput in this case becomes function of number of SUs and sensing time, given as:

$$R(N, T_s) = \frac{T - T_s - NT_r}{T}\begin{bmatrix} p(H_0)(1 - Q_f)C_0 + \\ p(H_1)(1 - Q_d)C_1 \end{bmatrix}. \text{(14)}$$

3.4 Optimum Fusion Rule

Different approaches are being used for optimal combining of decision at the fusion centre, among them TDC-CSS is discussed in this study. [9] proposed that TDC-CSS gives better performance than any other combining scheme.

For the optimum decision in the fusion centre, k out of N fusion rule is used. The fusion centre makes a decision that PU is present when k or more received decisions are made in support of presence of PU. The final detection and false alarm probability are given as:

$$Q_f = \sum_{i=k}^{N} \binom{N}{i} p_f^i (1 - p_f)^{N-i}, \qquad \text{....... (15)}$$

$$Q_d = \sum_{i=k}^{N} \binom{N}{i} p_d^i (1 - p_d)^{N-i}. \qquad \text{....... (16)}$$

In TDC-CSS, the sensing duration is extended as long as possible by fully utilizing the reporting block and without adding additional overhead in the mean time. For this, SU conduct sensing and reporting concurrently so that time consumed by reporting for one SU is also utilized for other secondary user's sensing [9].

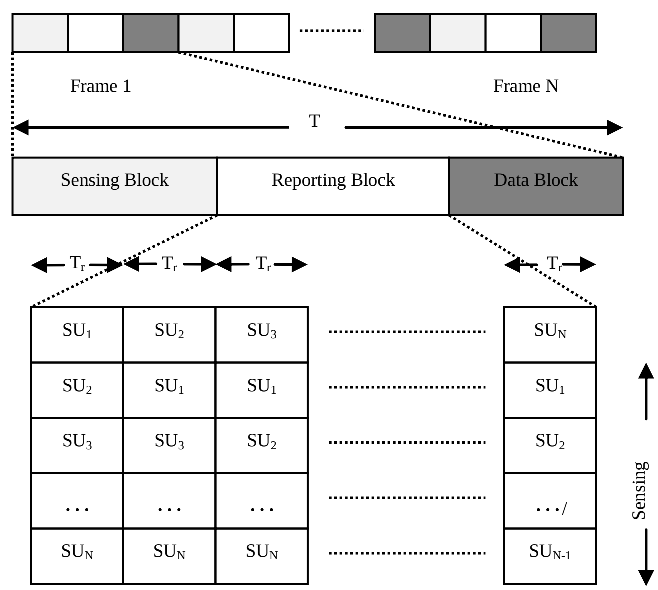

Figure 4: Frame structure for TDC-CSS [9]

The frame structure for TDC-CSS has been shown in Figure 4. This provides larger sensing time than that of the general frame structure shown in Figure 3. It can be seen that reporting duration for each SU is T_r and the sensing duration is $T_s+(N-1)T_r$. We assume that $T_s=T_r$. Thus sensing duration is NT_s.

To combine the multiple sensing results obtained from each SUs, it is assumed that whole sensing time is divided into N slots of duration Ts each. Using energy detection based spectrum sensing, false alarm and detection probabilities are given as:

$$p_f = Q\left(\frac{\lambda - \sigma_w^2 \sum_{i=1}^{N} u_i}{\sigma_w^2}\sqrt{\frac{T_s f_s}{2}}\right), \quad \text{.......(17)}$$

$$p_d = Q\left(\left(\frac{\lambda}{\sigma_w^2} - \sum_{i=1}^{N} u_i(|h_i|^2 \gamma + 1)\right)\sqrt{\frac{T_s f_s}{2(2\phi\gamma + 1)}}\right), (18)$$

where, $\phi = \sum_{i=1}^{N} u_i^2 |h_i|^2$. By combining (17) and (18), p_f is given as:

$$p_f = Q\left(\sqrt{2\phi\gamma+1}Q^{-1}(p_d) + \gamma\sqrt{\frac{T_s f_s}{2}}\sum_{i=1}^{N} u_i |h_i|^2\right). (19)$$

The maximum achievable throughput is given by [9] as:

$$R = \frac{T - T_s - NT_r}{T}\left(1 - Q_f\right)p(H_0)\log_2\left(1+\gamma_s\right) + \frac{T - T_s - NT_r}{T}\left(1 - Q_d\right)p(H_1)\log_2\left(1+\frac{\gamma_s}{1+\gamma}\right)$$

, ... (20)

where, γ_s is the SNR of the secondary link.

4. Results

In this section, the analysis presented above is verified. Throughput versus sensing time is plotted in different scenario. Simulation has been carried out with sampling frequency of 6 MHz, probability that the PU is absent, $p(H_0)$ =0.8, probability that PU is present, $p(H_1)$ =0.2, C_0 =6.6582, C_0 =6.6137 and frame duration, T of 100 ms.

The relationship of throughput with sensing time is shown in Figure 5. The graph has been obtained for SU number of 10, required detection probability of 0.9 and SNR of -20 dB. From this figure, it can be seen that the throughput of the system is maximum (3.75 Nats/sec/Hz) at sensing time of 25 ms.

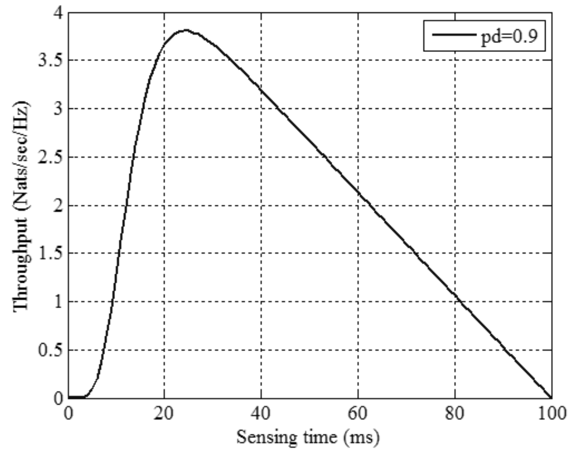

Figure 5: Throughput versus sensing time plot

This means that there exists an optimum value of sensing time for which, throughput of the system is maximum.

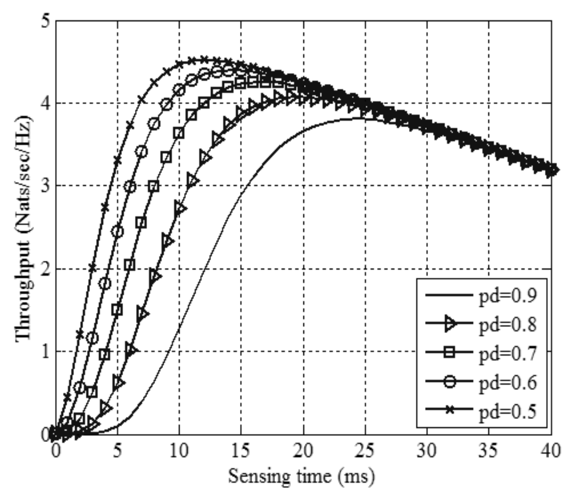

Figure 6: Sensing throughput tradeoff

Figure 6 shows the relationship of throughput with sensing time for different detection probabilities. For SU number of 10 and SNR of -20 dB, we can see that increasing required detection probability from 0.5 to 0.9 decreases the maximum throughput from 4.5 Nats/sec/Hz to 3.8 Nats/sec/Hz i.e. throughput of the system decreases with increasing required detection probability and vice-versa. This verifies the sensing throughput tradeoff as stated in [10]. Also, increasing throughput means there is more data transmission time and less sensing time within the fixed frame duration. Thus, for decreasing required detection probability, optimal sensing time also decreases.

The relationship of throughput with sensing time for different SU numbers has been simulated for required detection probability of 0.9 and SNR of -20 dB. The result has been shown in Figure 7.

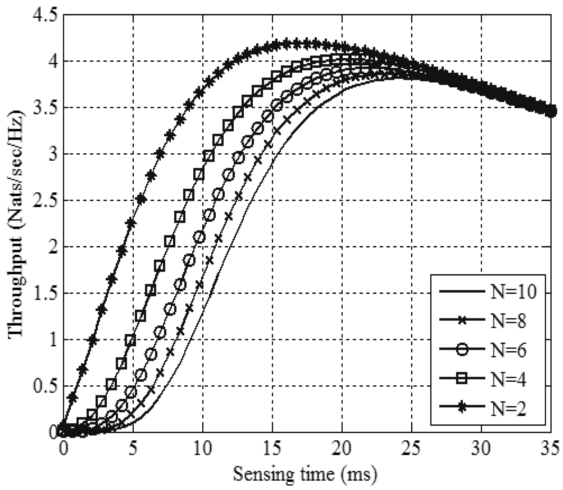

Figure 7: Throughput versus sensing time plot for different number of secondary users

We can see that for 2 SUs, maximum throughput is 4.25 Nats/sec/Hz. When SU number increases, maximum throughput decreases accordingly. This means throughput of the system increases with decreasing number of secondary users and vice-versa. This is because at less number of SUs, the total reporting delay becomes less so that there will be large amount of data transmission time available in the fixed frame duration. That means there exists a tradeoff between the throughput and number of SUs involved in cooperation.

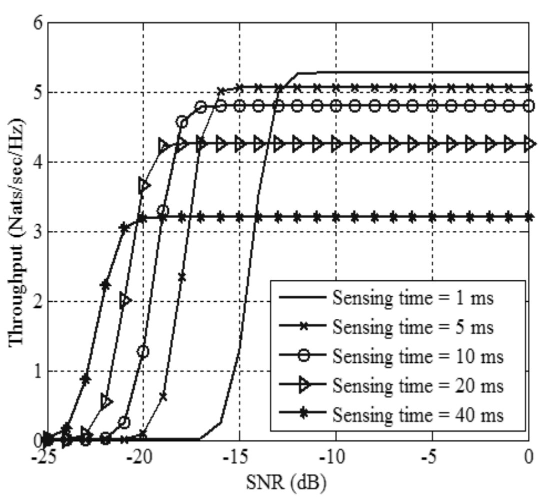

Figure 8: Throughput versus SNR plot for different sensing time

For a required detection probability of 0.9 and SU number of 10, the throughput and SNR relationship has been plotted for different sensing time values. The result has been obtained as shown in the Figure 8. For sensing time of 1 ms, the throughput of the system increases from 0 to maximum achievable value (5.25 Nats/sec/Hz) for increasing SNR from -25 dB to 0 dB. Also, increasing sensing time from 1 ms to 40 ms, maximum throughput decreases from 5.25 Nats/sec/Hz to 3.25 Nats/sec/Hz. This figure shows that throughput has direct relationship with SNR. The throughput of the system increases with increasing SNR value until maximum throughput is reached. For, increasing sensing time, maximum throughput decreases because increasing sensing time reduces data transmission time in the CR frame.

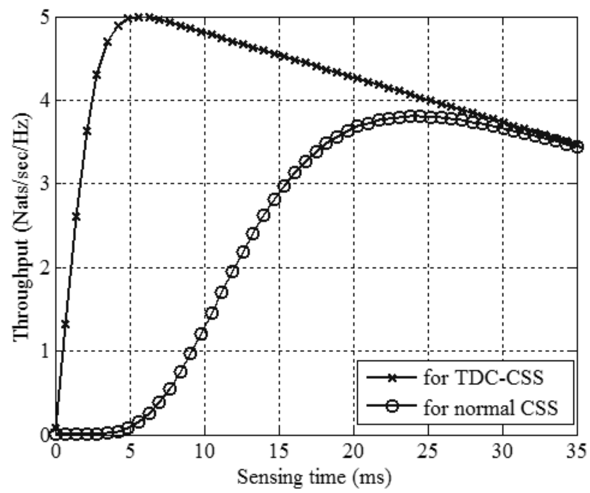

Figure 9: Throughput versus sensing time comparison for normal CSS and TDC-CSS

The comparative analysis of normal CSS and TDC-CSS in terms of throughput and sensing time has been shown in Figure 9. The simulation has been carried out for SU number of 10, required detection probability of 0.9 and SNR of -20 dB. It can be seen that the maximum throughput is 5 Nats/sec/Hz at 5 ms sensing time for TDC-CSS whereas it is 3.75 Nats/sec/Hz at 23 ms sensing time for normal combining scheme. That means, employing TDC-CSS will enhance the throughput by almost 32 %. Thus it can be said that the throughput of the system can be maximized by utilizing the reporting time for one CR user for the sensing purpose for another CR user.

4. Conclusion

From this work, it can be concluded that the throughput in cognitive radio can be enhanced by selecting the appropriate sensing time, selecting appropriate number of secondary users involved in spectrum sensing and selecting appropriate fusion rule at the fusion centre of the cognitive radio network. To verify the analysis, a simulation was set up; where energy detection based cooperative spectrum sensing method was used for spectrum sensing. Simulation results show that the sensing time of 25 ms would be appropriate for the modeled system. For secondary user number of 2, maximum achievable throughput is greatest (4.25 Nats/sec/Hz) i.e. for least number of secondary users, throughput would be maximum. Also using time domain combining-cooperative spectrum sensing, the maximum throughput of the system increases by 32% with sensing time allocation of 5 ms only.

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