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Performance Analysis of Throughput Maximization Techniques in Cognitive Radio Network Using Energy Detection Based Cooperative Spectrum Sensing

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Abstract

Throughput maximization is one of the major challenges in cognitive radio (CR) network. In this paper, two scenarios of throughput maximization are analyzed, which are: consideration of primary user (PU) protection and consideration of packet collision. In case of PU protection, throughput can be maximized by selecting either appropriate number of secondary users (SUs), or appropriate sensing time or appropriate fusion rule at the fusion center. In case of packet collision, optimum frame length is selected to maximize the throughput. Energy detection (ED) based cooperative spectrum sensing (CSS) is used as spectrum sensing method in all these techniques and time division combining (TDC) CSS is used as the appropriate fusion rule. To show the relationship of throughput with above parameters, a simulation is set up considering voice over internet protocol (VOIP) activity as PU activity. The simulation results verify that throughput can be enhanced by selecting proper sensing time, proper number of SUs, proper fusion rule and proper frame duration. For example: with decreasing the required detection threshold from 0.9 to 0.5, the throughput is increased by 19%. Also, decrease in reporting delay from 0.6 to 0 ms causes the increase in throughput by 20%. For a fixed reporting time, the throughput decreases by almost 18% with the increase of every 5 number of SUs. For every 20 ms increase in frame duration, the collision probability increases by 39% and throughput decreases accordingly. Using TDC-CSS, the throughput increases by about 31%.

Keywords: Spectrum sensing, throughput, energy detection, cooperation, primary user, secondary user, fusion center.

Introduction

The utile electromagnetic radio spectrum is a precious natural resource but it is of limited physical extent. However, wireless devices and applications are increasing day by day. Thus it is the fact that we are facing a difficult situation in wireless communications. Another fact is that, the licensed part of the radio spectrum is poorly utilized and thus a means of improved spectrum utilization is necessary[1]. Cognitive radio (CR) 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].

The SU repeatedly senses the spectrum to find the spectrum holes. The SU senses the channel each time before it transmits the data. When SU finds the unoccupied channel, it starts to transmit the data packet but problem arises when PU, which is the privileged user, wants to send the data packet during SU data transmission time. Not only this, the wrong sensing by the SU also affects the performance i.e. SU may also experience sensing error so that it may conclude that channel is vacant or occupied when actually not.

To address this situation, two cases have been considered in this study. In the first case, it is assumed that PU is sufficiently protected from interference considering high detection threshold. High detection threshold means that PU is detected more properly so that SU does not transmit during PU transmission. In the second case, it is assumed that PU is not sufficiently protected so that when SU is transmitting, PU comes back and transmits its own packets. During this time, there will be collision of packets between PU and SU.

When PU protection is considered, there are basically three approaches used to maximize the throughput in CR network, these are: selection of appropriate sensing time, selection of appropriate number of SUs in CR network and selection of appropriate fusion rule at the fusion center of the CR network. In CR network, the throughput gain of the network mainly depends on the throughput gain of SUs because the throughput of PUs is not expected to be affected by the SUs activities [3]. Thus in the PU protection case, basically throughput of secondary network is maximized.

When collision between PU and SU packets is considered, throughput of CR network depends on the collision interval which in turn depends on the length of the CR frame. Thus in this case, throughput is maximized in terms of CR frame duration.

Energy Detection (ED) method of spectrum sensing has been used in this research because the characteristics of primary signals are unavailable to the SUs but only presence or absence of signal power can be detected. In case of ED method, the received signal samples are used to calculate the energy of the signal. The energy is then compared to the threshold to decide upon the availability of the channel. If the calculated energy is less than the predefined threshold, the channel is assumed to be vacant otherwise the channel is assumed to be occupied. Since Cooperative spectrum sensing (CSS) improves the sensing performance, CSS has been applied to ED method[4]. In CSS, individual CR users sense the channel and send their sensing information to the network center (also called fusion center). The fusion center combines the sensing information received from different SUs by using a combining schemes and makes the final decision upon the availability of the channel.

There are three factors 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.

In CR network, the higher the probability of detection, the better the primary user is protected. However, from the SUs' perspective, the lower the probability of false alarm, the more chances the channel can be reused when it is available, thus the higher the achievable throughput for the secondary network. Thus designing the appropriate sensing duration is one of the major research interests to maximize the achievable throughput for the secondary network under the constraint that the primary users are sufficiently protected [5].

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 [6].

Related works

Throughput maximization is one of the major challenges in CR network. Regarding throughput maximization techniques, different researches are being done but there are basically two situations considered in every research.

First one is the consideration of PU protected from interference which are based on either selecting optimal number of SUs or the optimal sensing duration. Besides these two, optimal combining at the fusion center 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 center can be utilized by the second SU to sense the spectrum.

Second approach is the consideration of collision of packets between PU and SU. When SU senses the channel and finds idle, then it starts to transmit for the rest of the frame duration but when PU tries to send its own packet during that time, there will be collision between the packets from the PU and SU thus the throughput of the system will degrade.

Bayesian decision based fusion rule was applied to derive a new combining scheme at the fusion center of the CR network. The effect of this combining scheme on throughput was studied and it was concluded that the advanced combining scheme in the fusion center based on Bayesian decision rule provided better throughput as compared to AND, OR and MAJORITY decision rule [2]. The throughput of CR network was improved using ED based CSS where, at the fusion center, K out of N rule was used as the combining scheme[4]. Weighted summation method of fusion was used in the fusion center and ED based CSS was used to maximize the throughput[7]. The weighted sum of decision from different SUs was calculated at the fusion center 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. It was considered that cooperation enhances throughput but their result showed that increasing the number of SUs does not necessarily improve the throughput.

The concept of sensing throughput tradeoff was studied in different aspects. A broad view of sensing throughput tradeoff was given and it was shown that upon increasing the required detection probability, throughput of the system decreases and upon decreasing the required detection probability, throughput of the CR network increases[5]. Throughput and sensing time relationship was studied at low SNR and it was concluded that allocation of longer sensing time enhances the sensing performance but it does not enhance the throughput performance of the CR network[8]. Under the predefined detection probability (p_d), the throughput in case of both the cooperative and non cooperative spectrum sensing was studied and it was concluded that cooperative spectrum sensing gives better throughput performance[9]. Cumulative sum (CUSUM) algorithm, also known as quickest sensing algorithm to maximize the achievable throughput was proposed considering collision of packets between PU and SU[10]. VOIP traffic was first used there to verify the results.

Very unique approach of enhancing the throughput of CR network was proposed called TDC-CSS which improved throughput compared to classical CSS. The concept of this study was that there is a reporting delay in sending the SU decision upon the availability of channel to the fusion center. Thus the reporting delay for one SU can be employed for another SU as the sensing duration so that there will be better spectrum sensing. From the SU's perspective, better sensing means less false alarm and hence better use of the channel causing increase in throughput[11].

Iterative algorithm was used to find the optimum number of users in CR network for predefined number of iterations. Throughput was found maximum for small number of SUs involved in cooperation[12].

Performance analysis of throughput maximization techniques was done in narrow aspect[6]. In this study it was suggested that throughput can be enhanced by optimizing either sensing time or the number of SUs. The results have been verified in relation with Wi-Fi network.

Multiple PUs case was first considered to maximize the throughput of the CR network[3]. The case of imperfect spectrum sensing was considered where SU throughput was maximized and SU frame length was found.

Relationship of throughput in terms of packet collision between PU and SU was studied[13,14]. Collision throughput tradeoff was formulated, where throughput of the CR network was maximized in terms of collision probability [13]. The optimum length of CR frame was found in this case. Two scenarios viz. fixed allocation of channel and random allocation of channel were studied[14]. The throughput analysis was done in each of the cases.

The major contribution of this paper will be maximization of throughput in cognitive radio under different scenarios. Basically two cases, PU protection and collision is discussed in this paper. Optimum number of sensing time, optimum number of SUs and optimum frame length is found using TDC-CSS.

System Model

Let us consider a CR network consisting of a primary transmitter (P_{TX}) and M number of secondary users as shown below in Figure-1. Out of the M SUs, it is assumed that only N number of SUs is involved in CSS. That means N SUs simultaneously sense the presence or absence of the PU and send their decision to the fusion center. SUs use two separate channels for sensing and reporting. Sensing channel is used to detect the presence or absence of PU in the channel i.e. for spectrum sensing. Reporting channel is used to send the sensing information by each SU to the fusion center. Based on the results received from individual SUs through reporting channel, the fusion center uses one of the different methods of combining and makes the final decision upon the presence or absence of the PUs.

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).

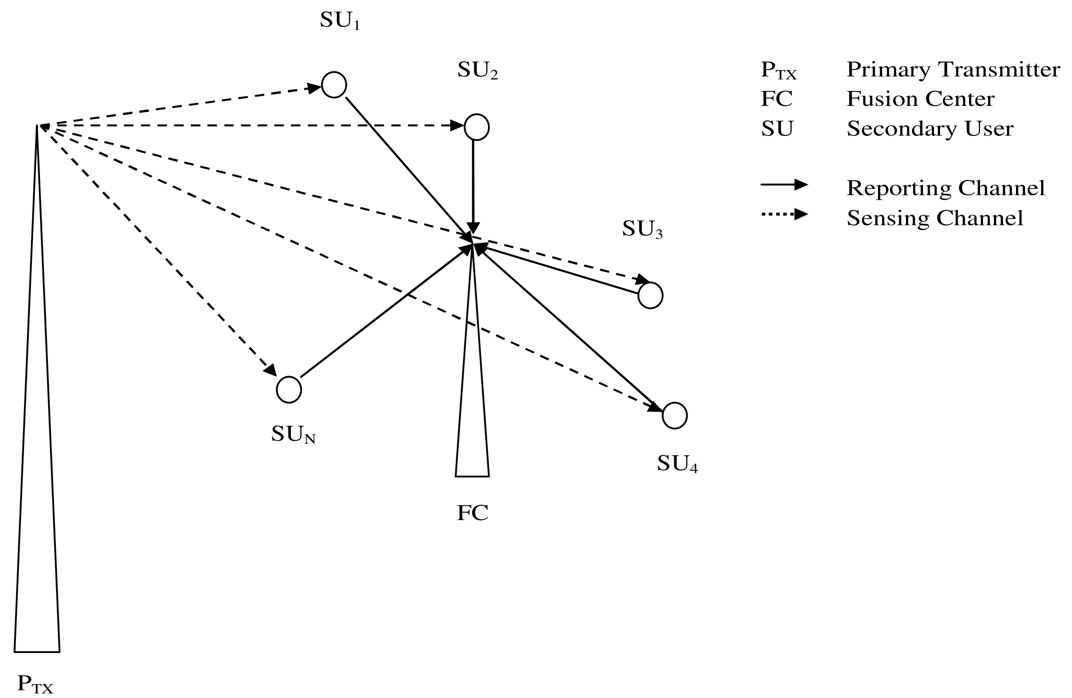


Figure-1
System model showing primary transmitter and SUs

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 center. Let θ denote the reporting error between the CR user and the fusion center, ζ denote the local decision bit and D denote the bit received by fusion center from the CR user. Then:

$$p\{D=0|\zeta=1\}=p\{D=1|\zeta=0\}=\theta \text{ and}$$
$$p\{D=0|\zeta=0\}=p\{D=1|\zeta=1\}=1-\theta . \quad (1)$$

Equivalent false alarm and detection probability are given as [11]:

$$\hat{p}_f = p_f(1-\theta)+(1-p_f)\theta \text{ and}$$
$$\hat{p}_d = p_d(1-\theta)+(1-p_d)\theta. \quad (2)$$

Frame Structure

Figure-2 shows the frame structure for cooperative spectrum sensing where each frame consists of three parts: a sensing block, a reporting block and a data transmission block. It is assumed that frame duration is T, sensing duration is Ts and individual reporting duration is Tr. In the sensing block, all the SUs conduct spectrum sensing simultaneously. In the reporting block, the local sensing results are reported to the fusion center sequentially via the reporting channel. Then, the fusion center makes the final decision to indicate absence or presence of the primary user[7,11].

Energy Detection: Energy detection is a method of spectrum sensing based on validating an assumption. In case of ED, the energy of received signal samples is calculated and compared with the predefined threshold. If the calculated energy exceeds the threshold, it is assumed that the channel is occupied by the PU and if the calculated energy is below the threshold level, it is assumed that the channel is empty. The block diagram of traditional energy detector has been shown in figure-3.

In case of CSS, every SU is involved in spectrum sensing using ED make some decision upon the presence or absence of PU. Decision result of each SU is sent to the fusion center, where the results are combined using one of the different combining schemes and final decision is made. It should be noted that there may be errors both in sensing the channel and reporting of the decision because the sensing and reporting channels are not perfect.

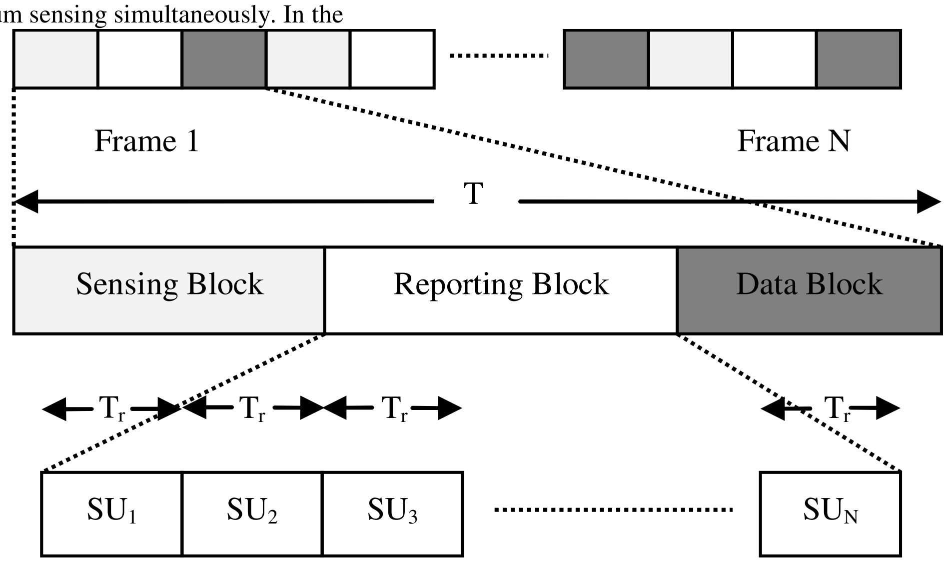
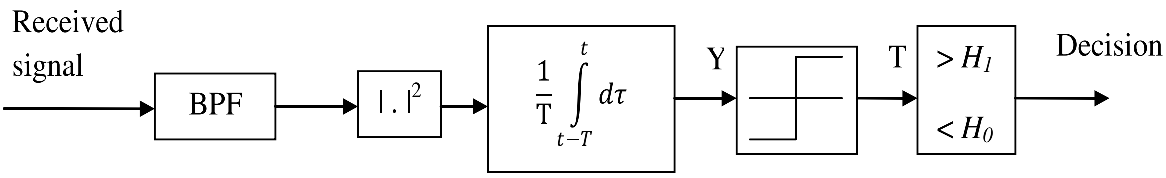


Figure-2
Frame structure for cooperative spectrum sensing



Figrue-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:

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

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 Figure-3 as:

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

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

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

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

Hence probability of false alarm, $p_f = p(T(y_i > \lambda | H_0))$, 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 [6]:

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

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

$$p_m = 1 - p_d \quad (8)$$

Here, λ is the decision threshold given as:

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

where, p_{th} is the minimum requirement of p_d.

Now overall false alarm probability (Q_f), overall detection probability (Q_d) and overall miss detection probability (Q_m) in cooperative spectrum sensing is given as:

$$Q_f = 1 - \left(1 - p_f\right)^N , \quad (10)$$

$$Q_d = 1 - \left(1 - p_d\right)^N \text{ and} \quad (11)$$

$$Q_m = \left(p_m\right)^N . \quad (12)$$

Optimum Number of Secondary 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:

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

where, $C_0 = \log_2(1+\gamma_s)$ and $C_1 = \log_2(1+\frac{\gamma_s}{1+\gamma})$ denote the throughput of CR network if operated in absence and presence of PU respectively, $p(H_0)$ and $p(H_1)$ are the probabilities that the PU is absent and present respectively. Here, γ_s is the SNR of the secondary link.

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

$$R(N,T_s) = \frac{T - T_s - NT_r}{T} \left[p(H_0)(1-Q_f)C_0 + p(H_1)(1-Q_d)C_1 \right]$$

(14)

Optimum Fusion Rule: Different approaches are being used for optimal combining of decision at the fusion center, among them TDC–CSS is being discussed in this research. TDC–CSS gives better performance than any other combining scheme[11].

For the optimum decision in the fusion center, k out of N fusion rule is used. The fusion center 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:

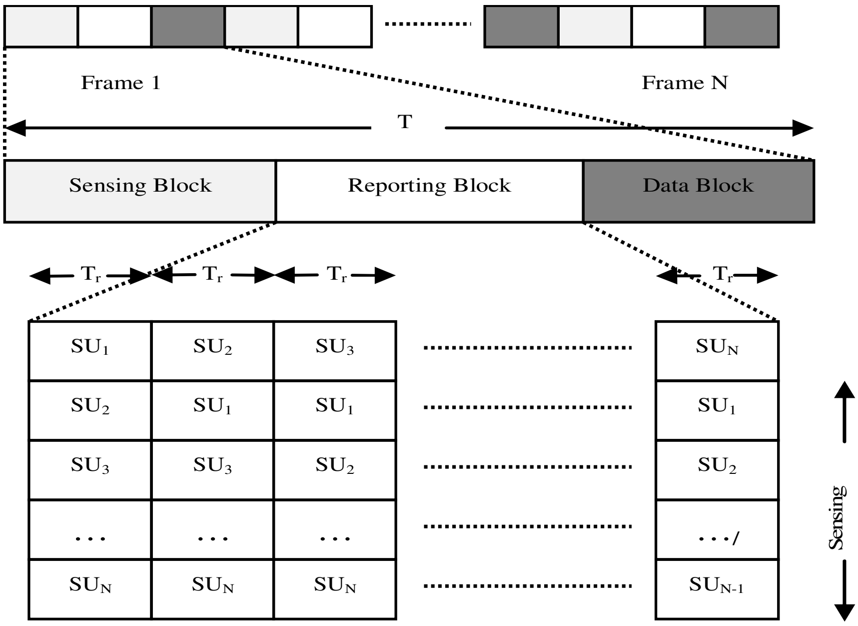


Figure-4
Frame structure for TDC–CSS

$$Q_f = \sum_{i=k}^{N} \binom{N}{i} p_f^i (1-p_f)^{N-i} \text{ and} \quad (15)$$

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

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 [11].

Figure-4 depicts the frame structure for TDC–CSS, which provides larger sensing time than that of the general frame structure as 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. It is assumed that T_s=T_r. Thus sensing duration is NT_s.

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

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

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

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

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

The maximum achievable throughput is given as [7]:

$$R = \frac{T - T_s - NT_r}{T}\left(1 - Q_f\right) p(H_0) \log_2\left(1 + \gamma_s\right) + \frac{T - T_s - NT_r}{T}\left(1 - Q_d\right) p(H_1) \log_2\left(1 + \frac{\gamma_s}{1+\gamma}\right). \quad (20)$$

Optimum Frame Duration to Minimize Collision: Let us assume a CR network which functions on a frame by frame basis as shown in Figure-2. During the frame interval T, the SUs sense the channel and report the decision to the fusion center within time $\tau = T_s + NT_r$. If no PU is detected in the channel, the SUs will use the remaining time of frame T – τ for data transmission. Otherwise, the SUs will not transmit in current frame and wait for the next frame and starts to sense the channel again.

It is assumed that PU has exponential distribution with active and idle periods denoted by β_1 and β_0 respectively [10]. Let us see the operation of CR network within a single frame. Since the

SUs do not transmit if there is the presence of a PU, it is plummy to find the throughput when the PU is not active at the time of sensing. However, the PU may become active any time and may cause collision between the PU and SU packets. Let P_C^S be the collision probability that SU experiences the collision during its data transmission interval of T – τ. Then throughput of CR network is given as[13]:

$$R = \frac{T-\tau}{T}(1-P_c^s)C_1 \qquad (21)$$

For a given sensing time, the larger the frame duration, the longer the data transmission time T – τ. Also, the longer the frame duration, the more chances that the PU becomes active, thus more collision of packets between PU and SU may occur, which degrades the throughput. Thus there exists an optimum frame duration for which collision of packets is minimum and throughput of the CR network is maximum.

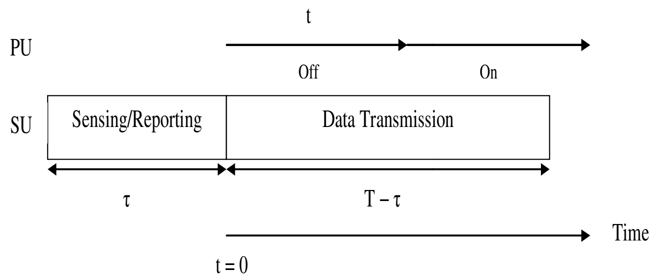


Figure-5
CR frame when PU is not active during sensing/reporting

Consider the transmission of a CR user's frame as shown in Figure-5 when no PU is present during the sensing slot[13]. The throughput of SU i.e. number of transmitted collision free packets will depend on when the PU turns on during the current frame. Let t be the time required for the PU to become active from idle state and the end of the sensing slot denote the starting point of time t = 0. Hence:

$$P_C^S = 1 - \frac{\beta_0}{T-\tau}\left(1-\exp\left(-\frac{T-\tau}{\beta_0}\right)\right), \qquad (22)$$

$$R = \frac{\beta_0}{T}\left(1-\exp\left(-\frac{T-\tau}{\beta_0}\right)\right)C_1 . \qquad (23)$$

To verify the mathematical model presented above, VOIP packets are considered as PU packets. VOIP traffic is exponentially distributed with mean idle time of 650 ms and mean active time of 352 ms[10].

Results

In this section, our analysis has been verified considering the case of VOIP packets. Although various parameters of the simulation have been changed but the basic parameters are: sampling frequency (f_S) = 6 MHz ($>2\times(1/T_S)$), average PU idle duration (β_0) = 650 ms, average PU active duration (β_1) = 352 ms, probability that the PU is absent, $p(H_0)$ = 650/(650+352) = 0.6487, probability that PU is present, $p(H_1)$ =352/(650+352) = 0.3513, γ_S = 20 dB and γ=-15 dB, $C_0 = \log_2(1+\gamma_S) = 6.6582$, $C_1 = \log_2(1+\frac{\gamma_S}{1+\gamma}) = 6.6137$.

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 throughput of the system increases with decreasing required detection probability and vice-versa. For the detection probability of 0.9, maximum achievable throughput is 3.085 bits/sec/Hz at 24 ms sensing time and for the detection probability of 0.5, it is 3.667 bits/sec/Hz at 12 ms sensing time and so on. That means, decreasing the required detection probability from 0.9 to 0.5, maximum achievable throughput almost increases by 19%. This is because for high detection probability threshold, larger sensing time has to be allocated for better sensing so that the data transmission time is less hence throughput is low. Upon decreasing the detection threshold, less sensing time will be sufficient to achieve that threshold so that data transmission time is high and hence larger throughput. This verifies the sensing throughput tradeoff [5].

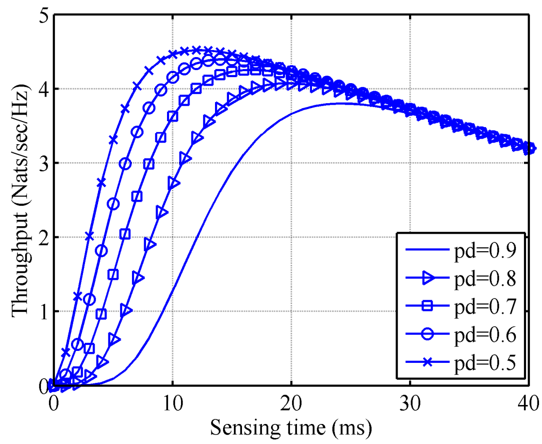


Figure-6
Throughput versus sensing time plot for different detection thresholds

Figure-7 shown below is the relationship of throughput with number of SUs for different reporting times. For required detection probability of 0.9 and SNR of -20 dB, we can see that throughput of the system increases with increasing the number of SUs until it reaches a maximum achievable value. After this point, throughput starts to decrease slowly. This is because at less number of CR users, the cooperative spectrum sensing is better so that the SUs can better use the channel hence the throughput is increasing. However, further increasing number of SUs decreases the throughput because at large number of SUs, the overall reporting delay becomes large. Also from this figure, we can see that for zero reporting delay, the maximum achievable throughput (3.87 bits/sec/Hz) is almost constant on increasing number of SUs from 15. This is because for a predefined sensing time and frame duration, zero reporting time means constant data transmission time and hence constant throughput. Also increasing the reporting delay from 0 ms to 0.6 ms, the maximum achievable throughput decreases from 3.87 bits/sec/Hz to 3.064 bits/sec/Hz i.e. decrease in throughput by about 20% which indicates increasing reporting delay decreases the throughput of the CR network. For a particular reporting time, the throughput decreases by almost 18% with increasing every 5 SUs.

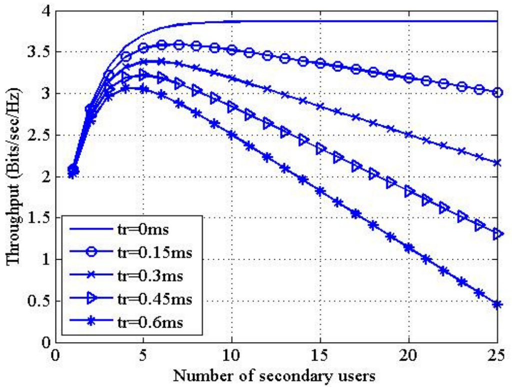


Figure-7
Throughput versus number of secondary users plot for different reporting times

For a required predefined sensing time of 20 ms, reporting time equal to sensing time and SU number of 10, the throughput and SNR relationship has been plotted for different detection probabilities. The result has been obtained as shown below in the figure-8. 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 decreasing detection threshold, the throughput is increasing for a particular value of SNR. The reason is similar as already explained in sensing throughput tradeoff case.

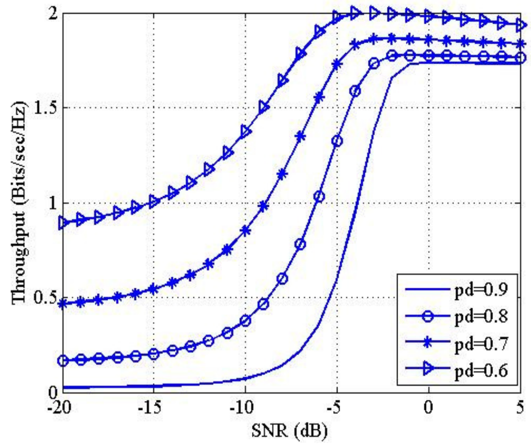


Figure-8
Throughput versus SNR plot for different detection probabilities

The comparative analysis of normal CSS and TDC-CSS in terms of throughput and sensing time has been shown below 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 in both cases. We can see that the maximum throughput is higher in case of new combining using TDC-CSS than that of normal combining scheme. Also maximum throughput in case of TDC-CSS (4.063 bits/sec/Hz) has been obtained at less sensing time (6 ms) compared to normal CSS (3.085 bits/sec/Hz at 24 ms sensing time). That means using TDC-CSS, a throughput enhancement of almost 31% can be obtained. 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.

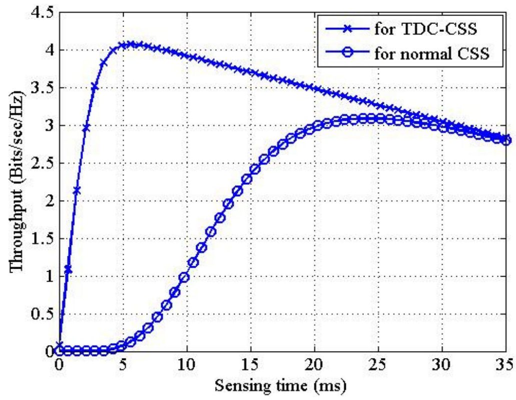


Figure-9
Throughput versus sensing time comparison between TDC-CSS and normal CSS

Considering VOIP traffic, packet collision probability of PU and SU versus frame duration has been plotted in Figure-10. For the case of VOIP traffic, average PU idle time is β_0= 650 ms and average PU active time is β_1= 352 ms with PU arrival time being exponentially distributed [10]. In this case sensing and reporting time is assumed to be completed within 1 ms. The result shows that the packet collision probability is directly dependent on frame duration because longer frame duration means longer time for PU to come back and transmit packets, so that there will be larger number of collision of packets between PU and SU. For every 20 ms increase in frame duration, the collision probability increases by 39%.

For the case of VOIP traffic with β_0= 650 ms and β_1 = 352 ms with sensing and reporting time assumed to be completed within 1 ms, the throughput and frame duration relationship has been plotted as shown in figure-11. This result shows that for small frame duration, increasing frame duration increases the throughput because for fixed sensing time; there will be large data transmission time. However, for large value of frame duration, it is more probable that PU comes back and transmits the packets so that there will be collision of packets and hence the throughput of the CR network will decrease. Thus there exists an optimum frame duration for which throughput of the CR network is maximum. In this simulation, maximum throughput of 6.26 bits/sec/Hz has been obtained at frame duration of 38 ms. The throughput remains within 1% of maximum value for frame duration of 20 to 60 ms.

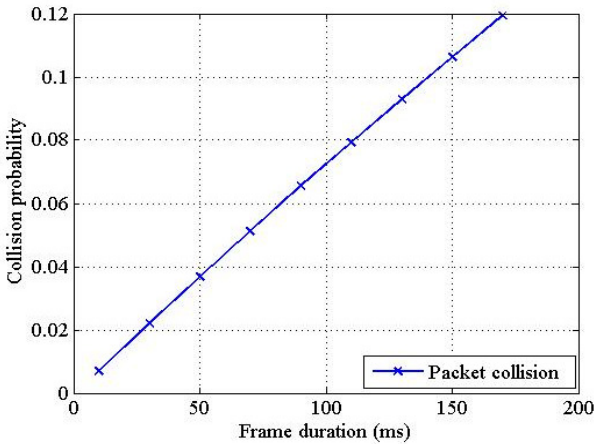


Figure-10
Collision probability versus frame duration plot for packet collision condition

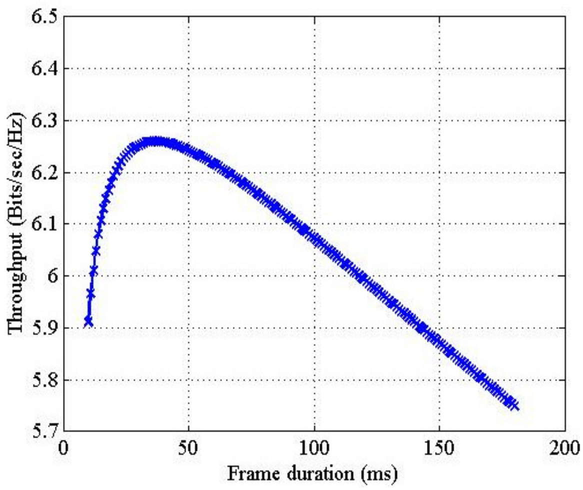


Figure-11
Throughput versus frame duration plot for packet collision condition

Conclusion

In this paper, two scenarios of throughput maximization have been considered, first one is the consideration of PU protection and second one is the consideration of packet collision. To achieve PU protection, a high detection threshold was set and optimum number of SUs and optimum sensing time was found. TDC-CSS was used as enhanced combining scheme. For packet collision, optimum frame length was found that maximized throughput and minimized the packet collision. The simulation was run considering voice VOIP activity as PU activity. The simulation results verify that throughput can be enhanced by selecting proper sensing time, proper number of SUs, proper fusion rule and proper frame duration. For example: with decreasing the required detection threshold from 0.9 to 0.5, the throughput increased by 19%. Also, decrease in reporting delay from 0.6 to 0 ms caused the increase in throughput by 20%. For a fixed reporting time, the throughput decreased by almost 18% with the increase of every 5 number of SUs. For every 20 ms increase in frame duration, the collision probability increased by 39% and throughput decreased accordingly. Using TDC-CSS, the throughput increased by about 31%.

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