Comparative Analysis of Time and Frequency Division Spectrum Sensing Frameworks in Cognitive Radio Network

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Summary
This paper provides comparative analysis of time and frequency division based spectrum sensing frameworks for single channel point to point communication links in Cognitive Radio Network (CRN). In Time Division Spectrum Sensing Frameworks (TDSSF) the unlicensed (secondary) user senses the spectrum periodically. The periodic sensing interrupts secondary user's (SU's) data transmission which results in its low throughput and also leads to high missed detection probability which causes interference to the licensed (primary) users. To address the limitations of the TDSSF, a Frequency Division Spectrum Sensing Frameworks (FDSSF) may be used which supports continuous spectrum sensing. In FDSSF a part of the spectrum is used for continuous spectrum sensing and the remaining part of the spectrum is used for SU data transmission. The simulation results show that for target probability of detection 0.5, throughput-oriented-FDSSF for K=2 gives 1.45 dB, 5.2 dB and 5.65 dB primary user's SNR gains over delay-oriented-FDSSF, multi-slot-TDSSF and single-slot-TDSSF respectively. In perspective of SU throughput for SU's SNR= 5 dB, throughput-oriented-FDSSF gives 9.09%, 30.6% and 36.92% higher throughput as compare to delay-oriented-FDSSF, multi-slot-TDSSF and single-slot-TDSSF respectively.

Key words:
Cognitive radio network, spectrum sensing framework, detection probability, false alarm probability, throughput.

1. Introduction

The radio frequency bands are a limited natural resource and are being licensed to service providers to meet growing demand of the wireless communication applications. Many of the existing wireless communication technologies support Non-Line-of-Sight (NLOS) communication to provide better quality of service. Due to considerable amount of absorption of very high frequency signals (above 4 GHz) by water drops in the environment / rain, scattering and shadowing [1] of the signal due to obstacles in the environment, lower frequency bands are preferred for NLOS communication [2]. But the lower frequency bands already have been allotted by government agencies under static spectrum allocation policy. The static spectrum allocation policy allows licensed user (primary user) to use the licensed frequency band and bars unlicensed users (secondary users). A study by Federal Communication Commission (FCC) shows that most of the static licensed spectrums are underutilized varies from 15 % to 85%, which is function of geographical location and time [3].

Thus to overcome the spectrum scarcity and improve spectrum utilization efficiency, Joe Mitola and Gerald Maguire introduced a new communication technique known as cognitive radio network (CRN) in 1999 [4]. In CRN, when the allotted frequency band is not utilized by the primary user (PU) the unlicensed secondary users (SUs) can use the unutilized frequency band opportunistically without causing harmful interference to the PU [5,6].

In this paper we have done comparative analysis and simulated time division and frequency division based sensing frameworks for single channel point to point communication links in CRN. In TDSSF a frame is divided into sensing and data transmission time slots [7]. The SU senses the spectrum periodically and transmits its own data whenever it senses the channel idle. The periodic sensing by the SU interrupts its data transmission which results in low throughput. The periodic sensing by the SU also leads to high missed detection during data transmission time slot. To address the limitations of TDSSF, frequency division based FDSSF also have been proposed in literature [8]. The FDSSF allows continuous sensing in a portion of the target licensed frequency band and SU data transmission in the remaining frequency band in absence of primary signal. Hence, the continuous spectrum sensing in the part of the primary frequency band improves probability of detection and reduces false alarm probability. The high probability of detection and low false alarm probability result in better protection to PUs from interference caused by SUs and improves SU's throughput respectively. There are two variant of TDSSF namely as single-slot-TDSSF and multi-slot-TDSSF. Similarly, there are two variant of FDSSF namely as delay-oriented-FDSSF and throughput-oriented-FDSSF.

In section II analysis of different types of sensing frameworks is presented. The simulation results of the TDSSF, FDSSF and variants of these frame formats are presented in section III. The conclusions of the

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comparative analysis of spectrum sensing frameworks are given in section IV.

2. Spectrum sensing frameworks for point-to-point communication link

In CRN the SUs can access the licensed band using two main approaches: (i) the SUs are allowed to access a frequency band only when it is detected idle, and (ii) the SUs coexist with the PUs under the condition of protecting the latter from harmful interference. The single channel point-to-point CR network is shown in Fig. 1, which is composed of one CR transmitter (CR TX) and CR receiver (CR RX). The CR network opportunistically operates within the subband of point-to-point primary users (PU TX and PU RX pair) [9]. In this paper we have used CR and SU interchangeably.

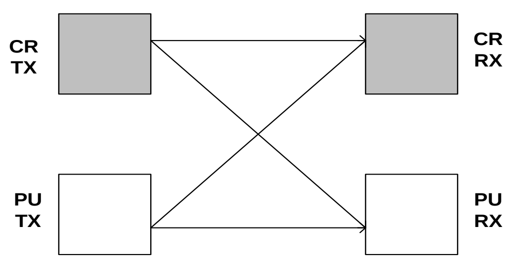

Fig. 1 Point-to-Point communication links in CRN

We make following assumptions:

- There are point-to-point communication links between PUs and SUs as shown in Fig. 1.
- SUs use energy-detector for spectrum sensing.

2.1 Single-slot Time Division Spectrum Sensing Framework (Single-slot-TDSSF)

In a frame of duration T, the CR TX spends τ seconds performing spectrum sensing as shown in Fig.2. If the CR TX detects that the considered channel is idle, then it utilizes the remaining frame duration T- τ seconds transmitting its data to the CR RX. If the CR TX detects that the considered channel is occupied by the PU TX, the CR TX doesn't transmit on that frequency band.

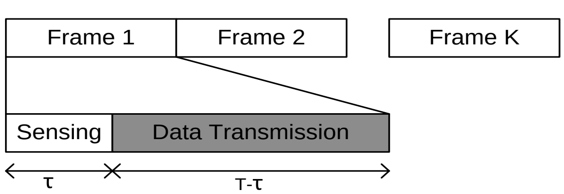

Fig. 2 Single-slot time division spectrum sensing framework.

For mathematical analysis of the sensing frameworks, let us assume that the discrete received signal at SU is represented as

$$y(n) = s(n) + w(n) \tag{1}$$

Where y(n) is the received signal, s(n) is the signal to be detected, w(n) is the additive white Gaussian noise sample and n is sample index. The decision test statics for energy detector can be written as

$$D = \sum_{n=1}^{N} |y(n)|^2 \tag{2}$$

The spectrum occupancy decision is made by comparing the decision test statics D with a threshold λ and distinguishing between following hypothesizes:

$$H_0 \; : \; y(n) = w(n) \tag{3}$$

$$H_1 \; : \; y(n) = s(n) + w(n) \tag{4}$$

Here the H_0 and H_1 represent hypothesizes corresponding to absence and presence of primary signal.

The performance parameters of the spectrum detectors are probability of detection P_d and probability of false alarm P_f [10]. These probabilities are formulated as

$$P_d = \Pr(D > \lambda | H1) \tag{5}$$

$$P_f = \Pr(D > \lambda | H0) \tag{6}$$

The P_d and P_f represent true and false detection of primary signal in the considered frequency band. Thus, large probability of detection and small false alarm probability are desired. The decision threshold λ can be selected in such a way that gives optimum values of P_d and P_f.
The probability of detection as an error function is approximated as:

$$P_d(\lambda, \tau) = Q\left(\left(\frac{\lambda}{N_0} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma + 1}}\right). \tag{7}$$

Where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{u^2}{2}\right)du$, the quantity γ is the received PU signal-to-noise ratio (SNR) at the SU, f_s is the sensing sampling and N_0 noise power at sensing receiver of the SU.
The mathematical analysis of the sensing-throughput tradeoff is given in [7, 11-14], which proves that the formulated problem has one optimal sensing time which gives the highest throughput for the secondary network. Similarly, the false alarm probability under Gaussian approximation is given by:

$$P(\lambda, \tau) = Q\left(\left(\frac{\lambda}{N_0} - 1\right)\sqrt{\tau f_s}\right) \tag{8}$$

The probabilities of detection (P_d) and false alarm (P_f) for target probabilities of false alarm ($\bar{P}_f$) and detection ($\bar{P}_d$) are given respectively as:

$$P_d(\tau) = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(\bar{P}_f) - (\gamma+1)\sqrt{\tau f_s}\right)\right) \quad (9)$$

$$P_f(\tau) = Q\left(Q^{-1}(\bar{P}_d)\sqrt{2\gamma+1} - \sqrt{\tau f_s}\right) \quad (10)$$

For SU throughput analysis, let P_s is the received power of SU, P_p is the interference power of primary user measured at the secondary receiver, N_0 is noise power and assume that PU's and SU's signals are Gaussian, white and independent of each other.

There are two scenarios for which the secondary network can operate at PU's frequency band.

Scenario I: When the primary user is not present and false alarm is not generated by the SU, the achievable data rate of the secondary link is $\frac{T-\tau}{T}R_0$. The probability to occur this scenario is $P(H_0)(1 - P_f(\lambda,\tau))$.

Scenario II: When the primary user is active but it is not detected by the SU, the achievable data rate of the secondary link is $\frac{T-\tau}{T}R_1$. The probability to occur this scenario is $P(H_1)(1-P_d(\lambda, \tau))$.

Then the achievable data rates are:

$$R_0 = W\log_2(1 + SNR_s) = W\log_2\left(1 + \frac{P_s}{N_0}\right) \quad (11)$$

and

$$R_1 = W\log_2\left(1 + \frac{SNR_s}{(1+SNR_p)}\right) = W\log_2\left(1 + \frac{P_s}{(P_p+N_0)}\right) \quad (12)$$

Now we define the throughput as

$$C_0(\lambda,\tau) = \frac{T-\tau}{T}R_0P(H_0)\left(1 - P_f(\lambda,\tau)\right) \quad (13)$$

and

$$C_1(\lambda,\tau) = \frac{T-\tau}{T}R_1P(H_1)(1 - P_d(\lambda,\tau)) \quad (14)$$

Then the average throughput for the secondary network is given by

$$C(\tau) = C_0(\lambda,\tau) + C_1(\lambda,\tau) \quad (15)$$

2.2 Multi-slot Time Division Spectrum Sensing Framework (Multi-slot-TDSSF)

To exploit time diversity in spectrum sensing in a frame, the sensing slot in each frame is split into multiple non-adjacent mini-slots as shown in Fig. 3.

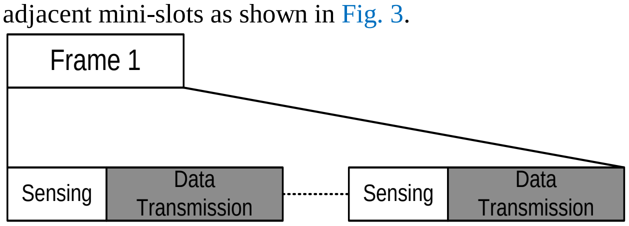

Fig. 3 Multi-Slot time division spectrum sensing framework

Let there are M number of mini-slots in a frame. Each mini-slot is of τ_1 duration. Hence, the total sensing duration in each frame is $\tau = M\tau_1$, and the number of sample for each mini-slot is $f_{s1}=f_s/M$. The measurements from M mini-slots are used to decide whether the primary user is active or not. The decision can be made using data and decision fusion methods. Complete mathematical model to determine probabilities of detection and false alarm are given in [7, 15] for data and decision fusion methods.

2.2.1 Data Fusion

Data of all mini-slots are processed jointly and then final decision is taken.Let $T_i(y)$ and $y_i(n)$ be the test statics and received signal in the i^{th} mini-slot respectively:

$$T_i(y) = \frac{1}{f_{s1}}\sum_{n=1}^{f_{s1}}|y_i(n)|^2, \quad (16)$$

Test statistic for final decision using data fusion is represented as

$$T(y) = \sum_{i=1}^{M} g_i T_i(y), \quad (17)$$

Where g_i is the weighting factor associated with i^{th} mini-slot. The probabilities of detection (P_d) and false alarm (P_f) for target probabilities of false alarm ($\bar{P}_f$) and detection ($\bar{P}_d$) are given respectively as:

$$P_d = Q\left(\frac{1}{\beta}\left(Q^{-1}(\bar{P}_f) - \gamma\sqrt{f_{s1}}\sum_{i=1}^{M} g_i|h_i|^2\right)\right) \quad (18)$$

$$P_f = Q\left(\beta Q^{-1}(\bar{P}_d) + \gamma\sqrt{f_{s1}}\sum_{i=1}^{M} g_i|h_i|^2\right) \quad (19)$$

Where $\beta = \sqrt{1 + \frac{2\gamma}{M}\sum_{i=1}^{M}|h_i|^2}$ given in [7] and h_i is the channel gain associated with i^{th} mini-slot.

The fading channels can be known or unknown.

- For known channel:

$$g_i = \frac{|h_i|^2}{\sqrt{\sum_{i=1}^{M}|h_i|^4}} \quad (20)$$

- For unknown channel:

$$g_i = \frac{1}{\sqrt{M}} \quad (21)$$

The probabilities of the correct and incorrect detection of the spectrum are $P(H_0)(1-P_f)$ and $P(H_1)(1-P_d)$. The corresponding throughputs are:

$$C_0(\lambda,\tau) = \frac{T-\tau}{T}R_0P(H_0)(1 - P_f) \quad (22)$$

and

$$C_1(\lambda,\tau) = \frac{T-\tau}{T}R_1P(H_1)(1 - P_d) \quad (23)$$

Then the average throughput for the secondary network is given by

$$C(\tau) = C_0(\lambda,\tau) + C_1(\lambda,\tau) \quad (24)$$

2.1.1 Decision Fusion

Data of each mini-slot is processed separately and individual decisions are made. The final decision is made by fusing the individual decisions of all mini-slots using logical OR, AND or majority (K-out-of-N) fusion rules [16, 17].

The probabilities of detection and false alarm at i^{th} mini-slot are given as [5]

$$P_d^{(i)} = Q\left(\left(\frac{\lambda}{N_0} - \gamma|h_i|^2 - 1\right)\sqrt{\frac{f_{s1}}{2\gamma|h_i|^2+1}}\right) \quad (25)$$

$$P_f^{(i)} = Q\left(\left(\frac{\lambda}{N_0} - 1\right)\sqrt{f_{s1}}\right) \quad (26)$$

- OR rule:

  The primary user is declared present if its signal is detected in at least one sensing mini-slot of a frame. The probabilities of detection and false alarm are given for OR rule as:

  $$P_d = 1 - \prod_{i=1}^{M}(1 - P_d^{(i)}) \quad (27)$$

  $$P_f = 1 - \prod_{i=1}^{M}(1 - P_f^{(i)}) \quad (28)$$

- AND rule:

  The primary user is declared present if its signal is detected in all sensing mini-slots of a frame. The probabilities of detection and false alarm are given for AND rule as:

  $$P_d = \prod_{i=1}^{M} P_d^{(i)} \quad (29)$$

  $$P_f = \prod_{i=1}^{M} P_f^{(i)} \quad (30)$$

- *K*-out-of-*N* rule :

  The primary user is declared present if its signal is detected in at least *K* out of *N* sensing mini-slots of a frame. The probabilities of detection and false alarm are given for K-out-of-*N* rule as:

  $$P_d = \sum_{k=K}^{N}\binom{N}{k}(P_d^{(i)})^k\left(1 - (P_d^{(i)})\right)^{N-k} \quad (31)$$

  $$P_f = \sum_{k=K}^{N}\binom{N}{k}(P_f^{(i)})^k\left(1 - (P_f^{(i)})\right)^{N-k} \quad (32)$$

2.3 Delay Oriented Frequency Division Spectrum Sensing Framework (DO-FDSSF)

The time division based periodic spectrum sensing over the entire PU spectrum interrupts the SU data transmission, which degrades throughput of the SU. The continuous sensing of the PU's spectrum improves spectrum detection probability. Therefore, to alleviate the SU interruption during its data transmission and to improve spectrum detection probability, the PU frequency band is divided into two subbands, one for opportunistic SU data transmission, and the other for continuous spectrum sensing [8] as shown in Fig. 4. The average SU transmission delay is reduced by selecting the proper bandwidth for spectrum sensing within each frame. Since different SUs may have different requirements on their quality of services, so the achievable average SU throughput is maximized by choosing the optimal sensing bandwidth within multiple adjacent frames.

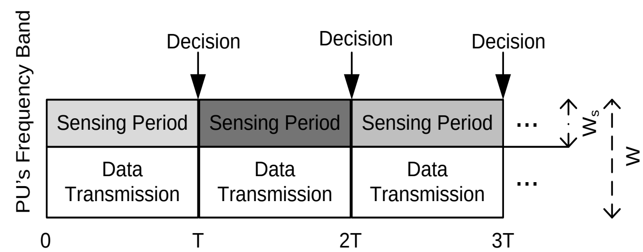

Fig. 4 Delay oriented frequency division spectrum sensing framework

The SU carries on spectrum sensing in sensing subband W_s continuously and transmits its data in remaining transmission subband $W\text{-}W_s$. The probabilities of false alarm and detection for the system model given in equations (3) to (6) for AWGN channel are formulated as function of sensing bandwidth W_s and frame duration T given as:

$$P_d(W_s) = Q\left(\frac{\lambda}{(1+\gamma)\sqrt{2TW_s}} - \sqrt{2TW_s}\right) \quad (33)$$

$$P_f(W_s) = Q\left(\frac{\lambda}{\sqrt{2TW_s}} - \sqrt{2TW_s}\right) \quad (34)$$

Here γ is the signal to noise ratio (SNR) of the PU signal observed at the SU receiver.

The probabilities of detection (P_d) and false alarm (P_f) for target probabilities of false alarm ($\bar{P}_f$) and detection ($\bar{P}_d$) are given respectively as:

$$P_d(W_s) = Q\left(\frac{1}{(1+\gamma)}\left(Q^{-1}(\bar{P}_f) - \gamma\sqrt{2TW_s}\right)\right) \quad (35)$$

$$P_f(W_s) = Q\left((1+\gamma)Q^{-1}(\bar{P}_d) - \sqrt{2TW_s}\right) \quad (36)$$

In the case of correct detection of spectrum opportunity only the SU transmits its data. The achievable SU throughput is

$$C_0(W_s) = (W - W_s)\, log_2(1 + \rho_1) \quad (37)$$

Here ρ_1 is the Signal to Noise Ratio (SNR) observed by the SU receiver over its transmission band.

$$\rho_1 = |h_s|^2\frac{N_s(W - W_s)}{N_0(W - W_s)} \quad (38)$$

Here h_s and N_S are channel gain and power spectral density of SU signal. The N_0 is noise power spectral density of AWGN channel.

In the case of incorrect detection of spectrum opportunity, the SU and PU transmit simultaneously. Thus, the SU receiver is interfered by the PU signal and the achievable throughput becomes

$$C_1(W_s) = (W - W_s)\log_2(1+\rho_2) \quad (39)$$

Here ρ_2 is the Signal to Noise and Interference Ratio (SINR) observed by the SU receiver over its transmission band.

$$\rho_2 = \frac{|h_s|^2 N_s (W-W_s)}{(N_p|h_p|^2+N_0)(W-W_s)} \quad (40)$$

Here h_p and N_p are channel gain and power spectral density of PU signals.

. The probabilities of the correct and incorrect detection of the spectrum are $P(H_0)(1-P_f(W_s))$ and $P(H_1)(1-P_d(W_s))$ respectively. The combined achievable throughput under the hypothesis of H_0 and H_1can be obtained as

$$C(W_s) = P(H_0)\left(1 - P_f(W_s)\right)C_0(W_s) + P(H_1)\left(1 - P_d(W_s)\right)C_1(W_s) \quad (41)$$

2.4 Throughput Oriented Frequency Division Spectrum Sensing Framework (TO-FDSSF)

Throughput oriented framework [8] is given in Fig. 5. The SU continuously senses many frames in sensing subband before taking final decision about presence of the PU. The long sensing duration improves spectrum detection probability and reduces false alarm probability which results in better protection to PU from interference from SUs and improved throughput of SU.

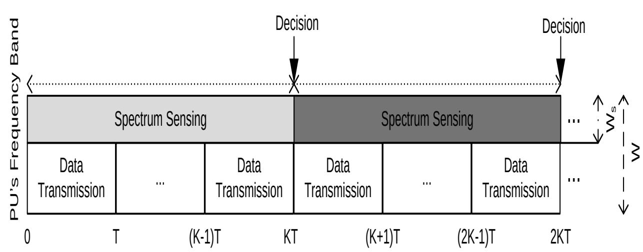

Fig. 5 Throughput oriented frequency division spectrum sensing framework

The probabilities of detection and false alarm for frequency division based continuous sensing for K frames to take final decision are given as:

$$P_d(W_s) = Q\left(\frac{\lambda}{(1+\gamma)\sqrt{2KTW_s}} - \sqrt{2KTW_s}\right) \quad (42)$$

$$P_f(W_s) = Q\left(\frac{\lambda}{\sqrt{2TKW_s}} - \sqrt{2KTW_s}\right) \quad (43)$$

The probabilities of detection (P_d) and false alarm (P_f) for target probabilities of false alarm ($\bar{P}_f$) and detection ($\bar{P}_d$) are given respectively as:

$$P_d(W_s) = Q\left(\frac{1}{(1+\gamma)}\left(Q^{-1}(\bar{P}_f) - \gamma\sqrt{2KTW_s}\right)\right) \quad (44)$$

$$P_f(W_s) = Q\left((1+\gamma)Q^{-1}(\bar{P}_d) - \sqrt{2KTW_s}\right) \quad (45)$$

The combined achievable throughput under the hypothesis of H_0 and H_1 is obtained using equation (41).

3. Simulation results and discussion

In this section, computer simulation results of different type of spectrum sensing frameworks analyzed in previous section are presented. In Table I, values of the parameters required in the simulation are given. For time division based spectrum sensing frameworks the sensing time 14.2ms is chosen corresponding to maximum throughput [7]. Similarly, for frequency division based spectrum sensing frameworks the sensing bandwidth 0.5 MHz is chosen corresponding to maximum throughput [8]. The comparison of the performance parameters of the spectrum sensing frameworks discussed in previous section are fair because these frameworks are simulated for optimum sensing time slot and sensing frequency subband, common constant simulation parameters given in Table I and common variables like PU's and SU's SNR.

Table 1 Simulation variables and values

Variable	Value
Frame duration (T)	100 ms
Sampling rate (f_s)	1MHz
Average Detection Probability ($\bar{P}_d$)	0.9
Average false alarm Probability ($\bar{P}_f$)	0.05
Band width	6 MHz
$P(H_1)$	0.3
$P(H_0)$= 1- $P(H_1)$	0.7

To compare probability of detection of the spectrum sensing frameworks, first we find the detection threshold for target false alarm probability $\bar{P}_f$ = 0.05 and detection threshold is used to determine probability of detection. Fig. 6 shows that probability of detection increases rapidly and attains the maximum value as the PU SNR increases. The frequency division based spectrum sensing frameworks give higher probability of detection as compare to time division based spectrum sensing frameworks which results in better protection to PU from the interference caused by SUs. Among the frequency division based sensing frameworks the TO-FDSSF for K=2 gives higher probability of detection as compare to DO-FDSSF. In case of time division based sensing frameworks, Multi-slot-TDSSF gives higher probability of detection as compare to Single-slot-TDSSF. The simulation results show that for target probability of detection 0.5, throughput-oriented-FDSSF for *K=2* gives 1.45 dB, 5.2 dB and 5.65 dB primary user's SNR gains over delay-oriented-FDSSF, multi-slot-TDSSF and single-slot-TDSSF respectively.

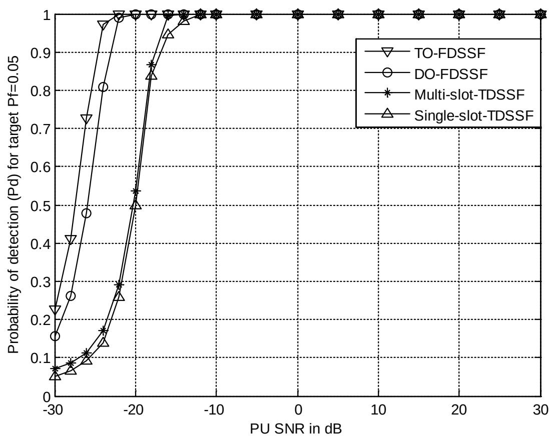

Fig. 6 Probability of detection versus SNR of PU

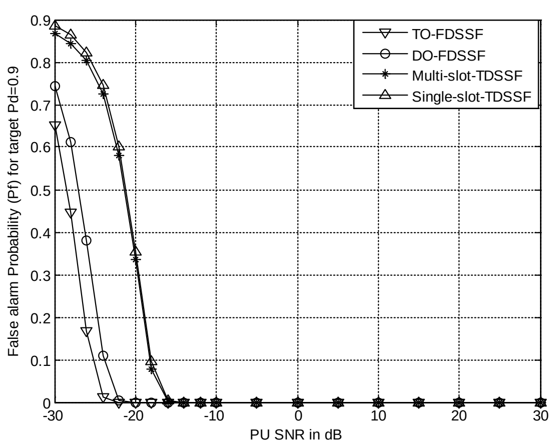

Fig. 7 Probability of false alarm versus SNR of PU

To compare probabilities of false alarm of the spectrum sensing frameworks analyzed in the previous section, we first find out detection threshold for target probability of detection $\bar{P}_d = 0.9$ and the detection threshold is used to determine the false alarm probability. Fig. 7 shows that probability of false alarm decreases rapidly and attains the minimum value as the PU SNR increases. The frequency division based spectrum sensing frameworks give higher probability of detection as compare to time division based spectrum sensing frameworks which results in better spectrum utilization by the SU by correct detection of available opportunities. Among the frequency division based sensing frameworks the TO-FDSSF for K=2 gives lower probability of false alarm as compare to DO-FDSSF. In case of time division based sensing frameworks, Multi-slot-TDSSF gives lower probability of false alarm as compare to Single-slot TDSSF.

To compare throughputs of the spectrum sensing frameworks analyzed in the previous section, we assume target probability of detection $\bar{P}_d = 0.9$ and corresponding false alarm probability is determined. The throughput of the analyzed spectrum sensing frameworks is calculated using the assumed and determined data in this section. Fig. 8 shows that SU throughput increases as the SU SNR increases for constant PU SNR= -20dB. The frequency division based spectrum sensing frameworks give higher throughput as compare to time division based spectrum sensing frameworks which shows better utilization of available opportunities by the SU. Among the frequency division based sensing frameworks the TO-FDSSF for K=2 gives higher throughput as compare to DO-FDSSF. In case of time division based sensing frameworks, Multi-slot-TDSSF gives higher throughput as compare to Single-slot-TDSSF. In perspective of SU throughput for SU's SNR= 5 dB, throughput-oriented-FDSSF gives 9.09%, 30.6% and 36.92% higher throughput as compare to delay-oriented-FDSSF, multi-slot-TDSSF and single-slot-TDSSF respectively.

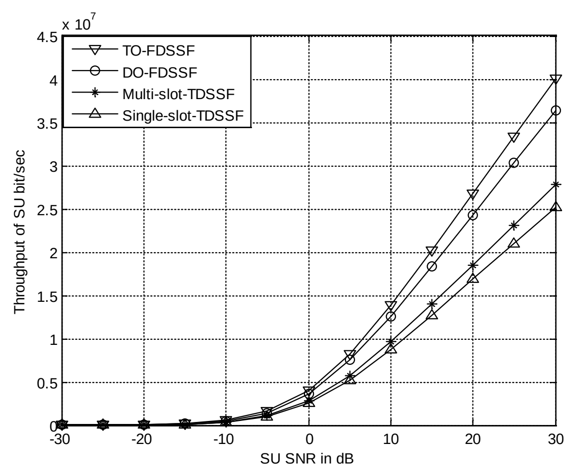

Fig. 8 SU's throughput versus SNR of SU for PU SNR= -20dB

4. Conclusion

The analysis of different types of spectrum sensing frame formats shows that as the spectrum sensing duration increase probability of detection increases and probability of false alarm decreases. The periodic spectrum sensing using TDSSF interrupts SU data transmission and reduces its throughput and missed detection during data transmission time leads to interference to the PU. Hence, the limitations of TDSSF may be addressed by FDSSF by continuous spectrum sensing on part of the PU frequency band. The continuous spectrum sensing using FDSSF improves probability of detection, reduces probability of false alarm and removes periodic interruption in SU data transmission. For further improvement in SU throughput a new spectrum sensing framework is need to be developed for simultaneous spectrum sensing and SU data transmission.

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