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Performance Enhancement in a Cognitive Radio Under a High Probability of Detection Constraint

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ABSTRACT

Cognitive radio is a new promising technology that aims to improve the spectrum scarcity problem in wireless communications by allowing use of unlicensed (secondary) users to frequency bands that are provided to licensed (primary) users, in a way which does not affect the quality of service (QoS) of the licensed networks [1], [2].In this paper we propose to improve the sensing-throughput tradeoff in OSA cognitive radio networks by performing spectrum sensing and data transmission at the same time. We also compare the average achievable throughput of the proposed cognitive radio system with the respective throughput of the conventional opportunistic spectrum access cognitive radio system in [12]. Finally it is shown that the proposed cognitive radio system exhibits improved throughput under a single high target detection probability constraint imposed for the protection of the primary users.

Keywords— Cognitive radio, opportunistic spectrum access,optimal power allocation, spectrum sensing, throughput maximization.

The word “Cognition” means the mental process of acquiring knowledge through thought, experience and the senses. Cognitive radio enables the users to determine portion of the spectrum available and detect the presence of licensed users when a user operates in licensed bands. There are four main cognitive tasks: spectrum sensing, spectrum management, spectrum mobility and spectrum sharing.

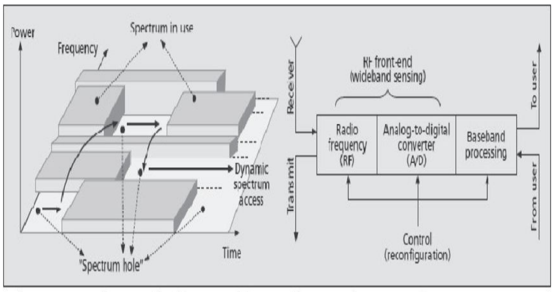

Fig. 1. Overview of cognitive radio: a) the spectrum hole concept; b) cognitive radio transceiver architecture.

Two main approaches have been proposed for cognitive radio so far, regarding the way that the cognitive radio users can access the licensed spectrum: (i) through opportunistic spectrum access (OSA) (ii) through spectrum sharing (SS).

The frame structure of the opportunistic spectrum access cognitive radio systems consists of a sensing time slot and a data transmission time slot, as depicted in Fig.2.

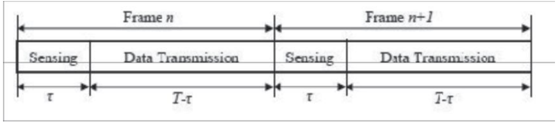

Fig.2 Frame structure of the conventional opportunistic spectrum access cognitive radio networks.

According to this frame structure, a secondary user ceases transmission at the beginning of each frame and senses for the status of the frequency band (active/idle) for τ units of time, whereas it uses the remaining frame duration $T - \tau$ for data transmission. Therefore, an inherent tradeoff exists in this frame structure between the duration of spectrum sensing and data transmission, hence the throughput of the cognitive radio system. According to the classical detection theory an increase in the sensing time results in a higher detection probability and lower false alarm probability, which in return leads to improved utilization of the available unused spectrum. However, the increase of the sensing time results in a decrease of the data transmission time, hence the achievable throughput. of the cognitive radio system. This sensing-throughput tradeoff was addressed in [12], where the authors studied the problem of finding the optimal sensing time that maximizes the average achievable throughput of an OSA cognitive radio system under a single high target detection probability constraint for the protection of the QoS of the primary users. In [13], the authors considered the ergodic throughput maximization of an OSA cognitive radio system under an interference power constraint and a single value high target detection probability constraint ($Ptar_d \approx 1$) and proposed an algorithm that obtains the sensing time and power allocation that maximizes the throughput of the cognitive radio system for Rayleigh fading channels.The paper is organised as follows :

Overcoming the sensing-throughput tradeoff in opportunistic spectrum access cognitive radio networks by performing spectrum sensing and data transmission at the same time. We compare the average achievable throughput of the proposed cognitive radio system with the respective throughput of the conventional opportunistic spectrum access cognitive radio system in [12].It is shown that the proposed cognitive radio system exhibits improved throughput under a single high target detection probability constraint imposed for the protection of the primary users.

I OVERVIEW OF THE SPECTRUM SENSING MODEL

(a) System Overview-

Let g and h denote the instantaneous channel power gains from the secondary transmitter (SU-Tx) to the secondary receiver (SU-Rx) and the primary receiver (PU-Rx), respectively. The channel power gains g and h are assumed to be ergodic, stationary and known at the secondary users similar to [8], [9], [13], [14], [15], [17], whereas the noise is assumed to be circularly symmetric complex Gaussian (CSCG) with zero mean and variance σ^2_n namely $\mathcal{CN}(0, \sigma^2_n)$.It should be noted here that knowledge of the precise channel power gain h is very difficult to be obtained in practice and therefore our results serve as upper bounds on the achievable throughput of the cognitive radio system.

The proposed cognitive radio system operates as follows. In the beginning, an initial spectrum sensing is performed, in order to determine the status (active/idle) of the frequency band. When the frequency band is detected to be idle, the secondary transmitter accesses it for the duration of a frame by transmitting information to the secondary receiver. The latter decodes the signal from the secondary transmitter, strips it away from the received signal, and uses the remaining signal for spectrum sensing, in order to determine the action of the cognitive radio system in the next frame. At the end of the frame, if the presence of primary users is detected, namely if the primary users started transmission after the initial spectrum sensing was performed, data transmission will be ceased, in order to protect the primary users from harmful interference. In the opposite case, the secondary users will access the frequency band again in the next frame. Finally, the process is repeated.

(b) Receiver Structure-

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$$y = \theta x_p + x_s + n \qquad (1)$$

where θ denotes the actual status of the frequency band ($\theta = 1$ if the frequency band is active and $\theta = 0$ if it is idle), xp and xs represent the received (faded) signal from the primary users and the secondary transmitter, respectively, and finally n denotes the additive noise. The received signal y is initially passed through the decoder, as depicted in Fig. 4, where the signal from the secondary transmitter is obtained. In the following, the signal from the secondary transmitter is cancelled out from the aggregate received signal y, and the remaining signal is used to perform spectrum sensing

$$\tilde{y} = \theta x_p + n , \qquad (2)$$

This is the same signal that the secondary receiver would receive if the secondary transmitter had ceased data transmission, which is the conventional way that was proposed to perform spectrum sensing.

Here, instead of using a limited amount of time τ, the whole duration of the frame T can be used for spectrum sensing.

(c) Frame Structure

The frame structure of the proposed cognitive radio system is presented in Fig. 8 and consists of a single slot during which both spectrum sensing and data transmission are performed at the same time, using the receiver structure presented in the previous subsection. The advantage of the proposed frame structure is that the spectrum sensing and data transmission time are simultaneously maximized, whereas, more specifically, they are equal to the frame duration.

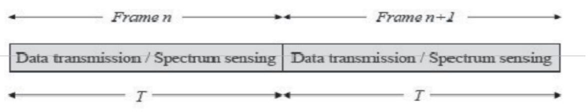

Fig.3 Frame structure of the proposed cognitive radio system.

The second important aspect is that the sensing time slot τ of the frame structure of Fig.3 is now used for data transmission, which leads to an increase in the throughput of the cognitive radio network on the one hand, and facilitates the continuity of data transmission on the other.

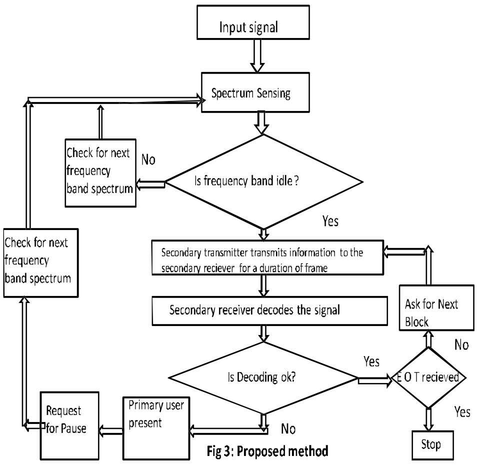

Fig. 4 Flow Chart of the proposed cognitive radio system.

II AVERAGE ACHIEVABLE THROUGHPUT OF THE PROPOSED COGNITIVE RADIO SYSTEM UNDER A HIGH TARGET DETECTION PROBABILITY CONSTRAINT

In this section, we study the average achievable throughput of the proposed cognitive radio system and compare it with the respective achievable throughput of the cognitive radio system that operates based on the conventional frame structure depicted in Fig. 2. We consider, similar to the work in [12], a single high target detection probability constraint for the protection of the primary users from harmful interference.

Considering the fact that the priority of a cognitive radio system is and should be the protection of the quality of service (QoS) of the primary network, a high target detection probability is required, in order to ensure that no harmful interference is caused to the licensed users by the secondary network. For instance, the target probability of detection in the IEEE 802.22 WRAN standard [5] is chosen to be 90% for a signal-to-noise ratio (SNR) as low as -20 dB for the primary user's signal at the secondary detector. We denote this target detection probability in the following by

$$P_d = Q\left(\left(\frac{\epsilon}{\sigma_n^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma+1}}\right) \quad (3)$$

$$P_{fa} = Q\left(\left(\frac{\epsilon}{\sigma_n^2} - 1\right)\sqrt{\tau f_s}\right)$$
$$= Q\left(\sqrt{2\gamma+1}\,Q^{-1}(P_d) + \sqrt{\tau f_s}\gamma\right) \quad (4)$$

where ϵ denotes the decision threshold of the energy detector

γ the received signal-to-noise ratio (SNR) from the primary user at the secondary detector,

τ denotes the sensing time

fs represents the sampling frequency.

Q is complementary distribution function of the standard Gaussian.

For a given target detection probability $P_d = \overline{P_d}$ the decision threshold ϵ is given by

$$\epsilon = \sigma_n^2\left(\sqrt{\frac{2\gamma+1}{\tau f_s}}\,Q^{-1}\left(\overline{P_d}\right) + \gamma + 1\right) \quad (5)$$

In the following proposition, we show that the probability of false alarm Pfa of the energy detection given by equation (4) is an increasing and concave function of the probability of detection Pd for $Pd \geq 0.5$, two properties that will be discussed further in the analysis.

Proposition 1: The probability of false alarm Pfa under the energy detection scheme given by equation (4) is an increasing function of the probability of detection Pd and is also a concave function of the probability of detection Pd for $Pd \geq 0.5$.

By setting $\alpha = \sqrt{2\gamma+1}$ and $\beta = \sqrt{\tau f_s}\gamma$ in equation (4) the false alarm probability $\mathrm{P_{fa}}$ is given by

$$P_{fa}(P_d) = Q(\alpha\, Q^{-1}(P_d) + \beta)$$

In order to prove that the probability of false alarm Pfa is an increasing function of the probability of detection Pd, we take the derivative of the probability of false alarm with respect to the probability of detection. The latter is given by

$$\frac{dP_{fa}}{dP_d} = \frac{d}{dP_d}[Q(\alpha Q^{-1}(P_d) + \beta)]$$
$$= \left\{-\frac{1}{\sqrt{2\pi}}\,exp\left(-\frac{[\mathrm{\alpha Q^{-1}(P_d)+\beta}]^2}{2}\right)\right\}.\left[\frac{d}{dP_d}[\alpha Q^{-1}(P_d) + \beta]\right]$$
$$= -\frac{\alpha}{\sqrt{2\pi}}\,exp\left\{-\frac{[\mathrm{\alpha Q^{-1}(P_d)+\beta}]^2}{2}\right\}.\frac{dQ^{-1}(P_d)}{dP_d} \quad (6)$$

Considering that $\mathrm{Q^{-1}(P_d)} = \sqrt{2}\,erf^{-1}(1-2P_d)$

We have $\frac{dQ^{-1}(P_d)}{dP_d} = \sqrt{2}\ .\ \frac{d[erf^{-1}(1-2P_d)]}{dP_d}$

$$= -\sqrt{2\pi}\,exp\{[erf^{-1}(1-2P_d)]^2\} \quad (7)$$

$$\frac{dP_{fa}}{dP_d} = \alpha\,.\mathrm{exp}\left\{[erf^{-1}(1-2P_d)]^2 - \frac{1}{2}\,.\,[\mathrm{\alpha Q^{-1}(P_d) + \beta}]^2\right\} \quad (8)$$

Since $\alpha = \sqrt{2\gamma+1} > 0$ it results from (8) that $\frac{dP_{fa}}{dP_d} \geq 0$

And therefore the probability of false alarm $P_{fa}(P_d)$ is an increasing function of the probability of detection P_d.

Now, by taking the second derivative of the false alarm probability P_{fa} with respect to the detection probability P_d ,we have

$$\frac{d^2P_{fa}}{d\,P_d^2} = \alpha^2\,\frac{[\mathrm{\alpha Q^{-1}(P_d)+\beta}]}{\sqrt{2\pi}}\left[\frac{dQ^{-1}(P_d)}{dP_d}\right]^2$$
$$.\,exp\left\{-\frac{[\mathrm{\alpha Q^{-1}(P_d)+\beta}]^2}{2}\right\} - \frac{d^2\,Q^{-1}(P_d)}{d\,P_d^2}.$$
$$.\frac{\alpha}{\sqrt{2\pi}}exp\left\{-\frac{[\mathrm{\alpha Q^{-1}(P_d)+\beta}]^2}{2}\right\}. \quad (9)$$

Where

$$\frac{d^2\,Q^{-1}(P_d)}{d\,P_d^2} = \frac{d}{dP_d}\left(-\sqrt{2\pi}\,exp\,\{[erf^{-1}(1-2P_d)]^2\}\right)$$
$$= -\sqrt{2\pi}\,exp\,\{[erf^{-1}(1-2P_d)]^2\}.$$
$$.\frac{d}{dP_d}([erf^{-1}(1-2P_d)]^2)$$

$$= -2\sqrt{2\pi}\ [erf^{-1}(1-2P_d)]\,\mathrm{exp}\{[erf^{-1}(1-2P_d)]^2\}.$$
$$.\frac{d}{dP_d}\left(erf^{-1}(1-2P_d)\right)$$
$$= 2\sqrt{2\pi}\,[erf^{-1}(1-2P_d)]\,\mathrm{exp}\{2[erf^{-1}(1-2P_d)]^2\}. \quad (10)$$

$$= 2\sqrt{2\pi}\,[erf^{-1}(1-2P_d)]\,\mathrm{exp}\{2[erf^{-1}(1-2P_d)]^2\}$$

Thus it results from the equations (7),(9) and (10) that the second derivative of the false alarm probability P_{fa} with respect to the detection probability P_d is finally given by

$$\frac{d^2P_{fa}}{d\,P_d^2} = \{\alpha[\mathrm{\alpha Q^{-1}(P_d) + \beta}] - \sqrt{2}\,erf^{-1}(1-2P_d)\}\,.$$

$$. \alpha\sqrt{2\pi}\, exp\left\{\frac{4\left[erf^{-1}(1-2P_d)\right]^2-\left[\alpha Q^{-1}(P_d)+\beta\right]^2}{2}\right\}$$
$$= \alpha\sqrt{2\pi}\left[(\alpha^2-1)Q^{-1}(P_d)+\alpha\beta\right].$$

$$. exp\left\{\frac{4\left[erf^{-1}(1-2P_d)\right]^2-\left[\alpha Q^{-1}(P_d)+\beta\right]^2}{2}\right\} \tag{11}$$

For a target detection probability

$$P_d \geq Q\left(-\frac{\alpha\beta}{\alpha^2-1}\right) \geq 0.5,$$

The second derivative of the false alarm probability P_{fa} with respect to the detection probability P_d from (11) turns out to be

$$\frac{d^2P_{fa}}{d\,P_d^2} \leq 0$$

Thus the probability of false alarm $P_{fa}(P_d)$ is a concave function of the detection probability P_d for $P_d \geq 0.5$.

We can now focus on the average achievable throughput of the cognitive radio system. The instantaneous transmission rate of the cognitive radio system when the frequency band is actually idle (H_0) is given by

$$r_0 = \log_2\left(1+\frac{gP}{\sigma_n^2}\right) \tag{12}$$

However, considering the fact that perfect spectrum sensing may not be achievable in practice due to the nature of wireless communications that includes phenomena such as shadowing and fading, we consider the more realistic scenario of imperfect spectrum sensing, where the actual status of the primary users might be falsely detected. Therefore, in this paper, we also consider the case that the frequency band is falsely detected to be idle, when in fact it is active (H_1). Following the approach in [15], [22], the instantaneous transmission rate in this case is given by

$$r_1 = \log_2\left(1+\frac{gP}{\sigma_n^2+\sigma_p^2}\right) \tag{13}$$

where σ_p^2 denotes the received power from the primary users.

The average achievable throughput of the cognitive radio system that operates based on the conventional frame structure of Fig. 2 is given by

$$\overline{R}(\tau) = \overline{R}_0(\tau) + \overline{R}_1(\tau) \tag{14}$$

Where $R_0(\tau)$ *and* $R_1(\tau)$ are given by

$$\overline{R}_0(\tau) = \frac{T-\tau}{T}P(H_0)\left(1-P_{fa}(\tau)\right)r_0 \tag{15}$$

$$\overline{R}_1(\tau) = \frac{T-\tau}{T}P(H_1)\left(1-P_d(\tau)\right)r_1 \tag{16}$$

respectively. In the equations above, T represents the frame duration, $P(H_0)$ the probability that the frequency band is idle, and $P(H_1)$ the probability that the frequency band is active. Under the proposed cognitive radio system, spectrum sensing is performed simultaneously with data transmission, whereas the sensing time and data transmission time are equal to the frame duration , as seen in Fig. 8. Therefore, the average achievable throughput of the proposed cognitive radio system is given by

$$\overline{C}=\overline{C_0}+\overline{C_1} \tag{17}$$

where $\overline{C_0}$ *and* $\overline{C_1}$ denote the average achievable throughput when the frequency band is actually idle and active (but falsely detected to be idle), respectively, and are given by

$$\overline{C_0} = P(H_0)\left(1-P_{fa}(T)\right)r_0 \tag{18}$$

$$\overline{C_1} = P(H_1)\left(1-P_d(T)\right)r_1 \tag{19}$$

respectively. For a target probability of detection $\overline{P_d}$ we can now show that the proposed cognitive radio system exhibits higher average achievable throughput compared to the cognitive radio system that operates based on the conventional frame structure shown in Fig. 2. Following the FCC requirements in [4], the secondary users should detect a worst-case SNR from the primary users, regardless if the spectrum sensing is performed at the receiver or the transmitter. This worst-case SNR is denoted here by $\overline{\gamma}$ From the classical detection theory [10], [11], it is known that for a target probability of detection $\overline{P_d}$, the higher the sensing time, the lower the probability of false alarm Pfa. Therefore, for a target probability of detection $P_d = \overline{P_d}$ sensing time $0 < \tau \leq T$, it results from the equation (4) that

$$\begin{aligned} P_{fa}(\tau) &= Q\left(\sqrt{2\overline{\gamma}+1}\,Q^{-1}(P_d)+\sqrt{\tau f_s\,\overline{\gamma}}\right) \\ &\geq Q\left(\sqrt{2\overline{\gamma}+1}\,Q^{-1}(\overline{P}_d)+\sqrt{Tf_s\,\overline{\gamma}}\right) \\ &= P_{fa}(T) \end{aligned} \tag{20}$$

Considering the fact that the complementary cumulative distribution function of the standard Gaussian (x) is a decreasing function of x. As a result, for a sensing time $0 < \tau \leq T$, it results from the equations (14)-(20) that

$$\begin{aligned} \overline{R}(\tau) &= \overline{R}_0(\tau) + \overline{R}_1(\tau) \\ &= \frac{T-\tau}{T}P(H_0)\left(1-P_{fa}(\tau)\right)r_0 + \frac{T-\tau}{T}P(H_1)\left(1-\overline{P}_d\right)r_1 \\ &< P(H_0)\left(1-P_{fa}(\tau)\right)r_0 + P(H_1)\left(1-\overline{P}_d\right)r_1 \\ &\leq P(H_0)\left(1-P_{fa}(T)\right)r_0 + P(H_1)\left(1-\overline{P}_d\right)r_1 \\ &= \overline{C_0}+\overline{C_1} = \overline{C} \end{aligned} \tag{21}$$

i.e. that the average achievable throughput of the proposed cognitive radio system for a target detection probability $P_d = \overline{P_d}$ is higher compared to the respective of the cognitive radio system that employs the frame structure depicted in Fig. 2, namely it results that

$$\overline{C} > \overline{R}(\tau) \tag{22}$$

for a sensing time $0 < \tau \leq T$.

III SIMULATION RESULTS

In this section, we present the simulation results for the proposed opportunistic spectrum access cognitive radio system using the energy detection scheme as a spectrum sensing technique. The frame duration is set to $T = 100$ ms, the probability that the frequency band is idle is considered to be $P(H0) = 0.6$, whereas the sampling frequency fs is assumed to be 6 MHz. The channels g and h are assumed to follow the Rayleigh fading model and more specifically, they are the squared norms of independent CSCG random variables that are distributed as $\mathcal{CN}(0, 1)$ and $\mathcal{CN}(0, 10)$, respectively. The average tolerable interference power at the primary receiver is considered to be $\Gamma = 1$ and the received SNR from the primary user is considered to be $\gamma = -20$ dB. As in [14], an additional channel power gain attenuation is considered here for the channel h between the secondary transmitter and the primary receiver, where an attenuation of 10 dB for example, means that $\{h\} = 1$.

In Fig. 5, the average achievable throughput versus the sensing time τ is presented for the proposed cognitive radio system (solid line) and the cognitive radio system that employs the conventional frame structure of Fig. 2 (dashed line), for the case of a single high target detection probability constraint . The received signal-to-noise ratio (SNR) from the secondary transmitter at the secondary receiver is considered to be SNR_S = 20 dB as in [12], the target probability of detection is set to $\overline{P_d}$ = 99.99%, in order to effectively protect the primary users from harmful interference, whereas different values of the target detection signal-to-noise ratio from the primary user (denoted by SNRp) are presented. It can be clearly seen that the average achievable throughput of the proposed cognitive radio system (solid line) is significantly higher compared to the respective achievable throughput of the cognitive radio system that employs the conventional frame structure of Fig. 2 (dashed line). This throughput improvement can be explained by the fact that the whole duration of the frame T is used for data transmission, as opposed to the conventional frame structure of Fig. 2, where only a part of the frame is used for data transmission (i.e. $T - \tau$). Moreover, the improved sensing capabilities of the proposed cognitive radio system also contribute to the throughput improvement of the cognitive radio system by enabling a more efficient usage of the available unused spectrum. More specifically, it can be seen from Fig. 5 and the equation (4) that for the same target probability of detection $\overline{P_d}$, the probability of false alarm Pfa for the optimal sensing time under the conventional frame structure is higher compared to the respective false alarm probability of the proposed cognitive radio system. The latter remark can be explained by the fact that the whole duration of the frame T is used for spectrum sensing in the proposed system, as opposed to merely a part of the frame under the conventional frame structure. In Fig. 6, the average achievable throughput is presented versus the target probability of detection $\overline{P_d}$, for a target detection signal-to-noise ratio from the primary user equal to SNR_P= -22dB. It can be clearly seen from Fig. 6 that the average achievable throughput under the proposed cognitive radio system is significantly higher compared to the respective achievable throughput of the system that employs the conventional frame structure whereas the decrease in the average achievable throughput as the target probability of detection $\overline{P_d}$ receives higher values is small, especially compared to the respective of the secondary users that employ the conventional frame structure of Fig. 2. This means that the proposed cognitive radio system can provide better protection for the primary users on the one hand, while achieving an increased throughput for its users on the other, even for very high values of target detection probability and very weak signals from the primary users. This can be further seen from Fig. 7, where the average achievable throughput from the primary users (SNRp), for a target probability of detection equal to $\overline{P_d}$ = 99.99%.

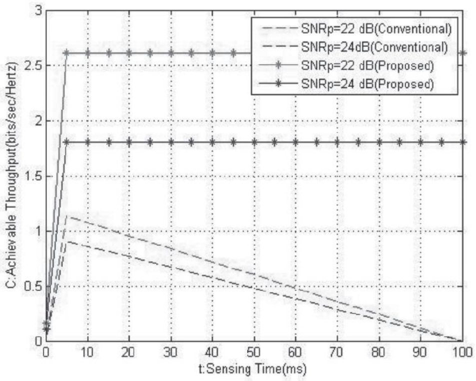

Fig. 5 Simulation Results of Average achievable throughput of the proposed and conventional opportunistic spectrum access cognitive radio system versus the sensing time t, for various values of the target detection SNR from the primary user (SNRp) and for a target detection probability $\overline{P_d}$ = 99.99%.

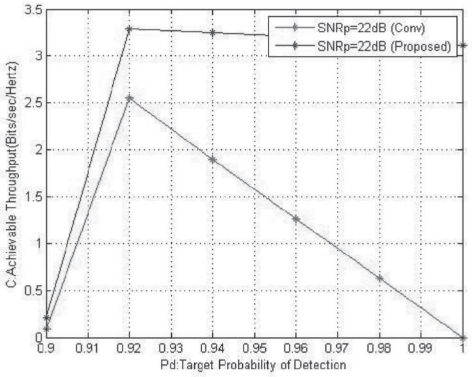

Fig.6. Average achievable throughput of the proposed and conventional opportunistic spectrum access cognitive radio system versus the target probability of detection $\overline{P_d}$ for various values of the target detection SNR from the primary user (SNRp).

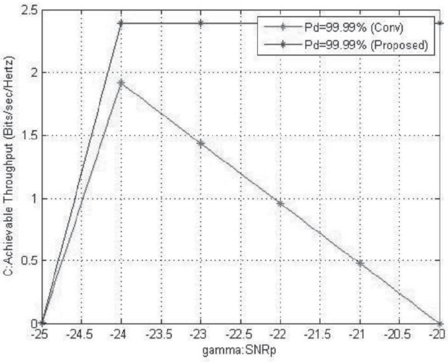

Fig. 7. Average achievable throughput of the proposed and conventional opportunistic spectrum access cognitive radio system versus the target detection SNR from the primary user (SNRp) for a target detection probability$\overline{P_d}$= 99.99%.

IV CONCLUSION

The proposed novel cognitive radio system is expected to improve the achievable throughput of opportunistic spectrum access by performing data transmission and spectrum sensing at the same time. More specifically, the average achievable throughput of the proposed cognitive radio system under a single high target detection probability constraint is expected that it can achieve significantly improved throughput compared to the respective conventional cognitive radio systems.

In addition, we studied the problem of maximizing the ergodic throughput under joint average transmit and interference power constraints, and proposed an algorithm that acquires the optimal target detection probability and power allocation strategy that is expected to maximize the ergodic throughput of the proposed cognitive radio system.

Furthermore, it is expected that for low values of channel power gain attenuation between the secondary transmitter and the primary receiver, a high target detection probability ($\overline{P_d}$ □ 1) will lead to the maximum achievable ergodic throughput, whereas for higher values of channel power gain attenuation, spectrum sensing not only does not provide better protection for the primary users, but it also has a negative effect on the achievable ergodic throughput of the cognitive radio system and should therefore be avoided.

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