Enhancing the Capacity of Spectrum Sharing Cognitive Radio Networks

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***Abstract*—Spectrum sharing has attracted a lot of attention in cognitive radio recently as an effective method of alleviating the spectrum scarcity problem by allowing unlicensed users to coexist with licensed users under the condition of protecting the latter from harmful interference. In this paper, we focus on the throughput maximization of spectrum sharing cognitive radio networks and propose a novel cognitive radio system that significantly improves their achievable throughput. More specifically, we introduce a novel receiver and frame structure for spectrum sharing cognitive radio networks and study the problem of deriving the optimal power allocation strategy that maximizes the ergodic capacity of the proposed cognitive radio system under average transmit and interference power constraints. In addition, we study the outage capacity of the proposed cognitive radio system under various constraints that include average transmit and interference power constraints, and peak interference power constraints. Finally, we provide simulation results, in order to demonstrate the improved ergodic and outage throughput achieved by the proposed cognitive radio system compared to conventional spectrum sharing cognitive radio systems.**

***Index Terms*—Cognitive radio, optimal power allocation, spectrum sensing, spectrum sharing (SS), throughput maximization.**

I. Introduction

According to recent measurements by the Federal Communications Commission (FCC), the current fixed spectrum allocation policy has resulted in several bands being severely underutilized both in temporal and spatial manner [1], while the need for more available spectrum to develop better wireless services becomes increasingly pressing. Cognitive radio [2], [3] is considered to be one of the most promising solutions to alleviate the spectrum scarcity problem and support the increasing demand for wireless communications by allowing unlicensed (secondary) users to access licensed frequency bands, under the condition of protecting the quality of service (QoS) of the licensed (primary) networks. The realization that the spectrum is not efficiently used under the current fixed spectrum allocation policy has recently led to the decision of the FCC to allow access of unlicensed users to the broadcast television spectrum at locations where that spectrum is not being used by licensed services [4].

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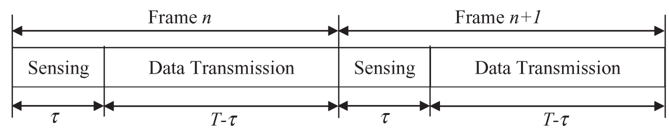

Fig. 1. Frame structure of conventional sensing-based spectrum sharing.

Two main approaches have been developed for cognitive radio so far, regarding the way a secondary user accesses the licensed spectrum: i) through opportunistic spectrum access (OSA), also known as interweave scheme, according to which a secondary user accesses a frequency band only when it is detected not being used by the primary users [5], and ii) through spectrum sharing (SS), also known as underlay scheme, based on which the secondary users coexist with the primary users under the condition of protecting the latter from harmful interference [6], [7]. Recently, a third hybrid approach was proposed, aiming to increase the throughput of the two aforementioned schemes, in which the secondary users initially sense for the status (active/idle) of a frequency band (as in the OSA) and adapt their transmit power based on the decision made by spectrum sensing, to avoid causing harmful interference (as in SS) [8]. The frame structure of this approach is the same as in the opportunistic spectrum access and consists of a sensing slot and a data transmission slot, as shown in Fig. 1.

A secondary user that employs this frame structure ceases data transmission at the beginning of each frame, performs spectrum sensing for τ units of time, in order to determine the status (active/idle) of the frequency band, and uses the remaining frame duration $T - \tau$ for data transmission. Therefore, an inherent tradeoff exists in this hybrid approach between the duration of spectrum sensing and data transmission. This tradeoff was studied in [8] and [9] for the ergodic throughput of cognitive radio networks and is similar to the one seen in opportunistic spectrum access cognitive radio networks [10]. The sensing-throughput tradeoff problem becomes very significant when the hybrid approach is used to increase the throughput of spectrum sharing cognitive radio networks, since the primary signals under detection are very weak and may therefore lead to very high sensing times that would have a detrimental effect on their achievable throughput. In addition, this frame structure disrupts the continuity of communication in spectrum sharing cognitive radio networks and results in a decrease of their throughput by a factor of $(T - \tau)/T$ when the primary users are active.

In this paper, we focus on the throughput maximization of spectrum sharing cognitive radio networks. We consider the hybrid approach as a method for improving the achievable throughput and propose a novel cognitive radio system that overcomes the sensing-throughput tradeoff problem. This is achieved by performing spectrum sensing and data transmission at the same time, which results in the maximization of both the sensing time and the data transmission time, hence the throughput of the cognitive radio network. This is analyzed in more detail in Section II. In addition, we study the problem of maximizing the ergodic throughput of the proposed cognitive system under average transmit and interference power constraints and propose an algorithm that acquires the optimal power allocation strategy that maximizes the system's ergodic throughput. Finally, we study the outage capacity of the proposed spectrum sharing cognitive radio system under various constraints, such as average interference power constraints, peak interference power constraints and average transmit power constraints, and compare it to the respective of the conventional spectrum sharing cognitive radio systems [11].

The rest of the paper is organized as follows. In Section II, we present the system model and introduce the proposed spectrum sharing cognitive radio system. In Section III, we study the problem of maximizing the ergodic throughput of the proposed cognitive radio system under joint average transmit and interference power constraints and propose an algorithm that acquires the optimal power allocation strategy. The outage capacity is studied in Section IV, whereas simulation results are presented in Section V. Finally, the conclusions are drawn in Section VI.

Notations: $\mathbb{E}\{\cdot\}$ denotes the expectation operation, vectors are boldface capital letters, the transpose of the vector $\mathbf{A}$ is denoted by $\mathbf{A}^T$, $[x]^+$ denotes $\max(0, x)$, $\log$ represents the natural logarithm, P denotes power, and finally, $\mathcal{P}$ denotes probability.

II. System Model and Proposed Spectrum Sharing Scheme

We consider the cognitive radio system presented in Fig. 2 that operates based on the proposed spectrum sharing scheme that is described in the following. 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 channels g and h are assumed to be ergodic, stationary and known at the secondary users as in [6], [8], [11]–[13], with probability density function (pdf) $f_g(g)$ and $f_h(h)$, respectively, whereas the noise is assumed to be circularly symmetric complex Gaussian (CSCG) with mean zero and variance σ_n^2, namely $\mathcal{CN}(0, \sigma_n^2)$.[1] It should be noted that in practice, it might be difficult to obtain perfect information of the channel h for fast fading channels. Nonetheless, our results serve as upper bounds for the achievable rate of practical cognitive radio systems, as in [6] and [11]. In the following, we describe how the proposed spectrum sharing scheme operates and present the receiver and frame structure employed in this cognitive radio system.

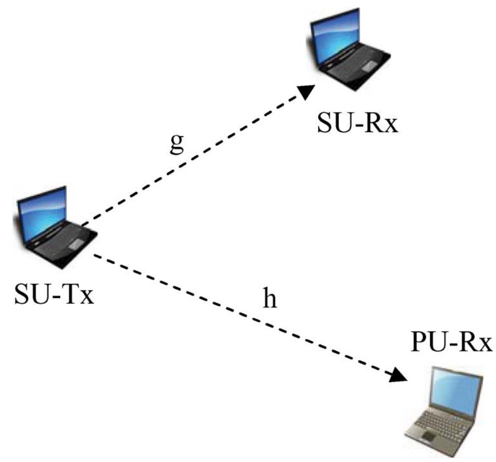

Fig. 2. System model.

A. System Overview

The proposed cognitive radio system operates as follows. In the beginning, an initial spectrum sensing is performed to determine the status of the frequency band. Based on the decision of spectrum sensing, the secondary users communicate using higher transmit power P_0 if the primary users are detected to be idle and lower transmit power P_1 otherwise. In the following, the secondary receiver decodes the signal sent by the secondary transmitter, strips it away from the received signal and uses the remaining signal to perform 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 status of the primary users has changed after the initial spectrum sensing was performed, the secondary users will change their transmit power from higher to lower or *vice versa*, based on the spectrum sensing decision (which is sent back to the transmitter via a control channel), in order to avoid causing harmful interference to the primary users. Finally, the process is repeated.

B. Receiver Structure

The receiver structure of the proposed cognitive radio system is presented in Fig. 3. The received signal at the secondary receiver is given by

$$y = \theta x_p + x_s + n \tag{1}$$

where θ denotes the actual status of the frequency band ($\theta = 1$ if the frequency band is active, whereas $\theta = 0$ if the frequency band is idle), x_p and x_s represent the received signal from the primary users and the secondary transmitter, respectively. Finally, n denotes the additive noise.

The received signal y is initially passed through the decoder, as depicted in Fig. 3, where the signal from the secondary transmitter is obtained.[2] In the following, the signal from

[1] In practice, the channel power gain h can be obtained via, e.g., estimating the received signal power from the PU-Rx when it transmits, under the assumptions of the pre-knowledge on the PU-Rx transmit power level and the channel reciprocity [18].

[2] In spectrum sharing cognitive radio systems, the secondary users are able to communicate effectively, irrespective of the status of the primary users [6], [11]–[13].

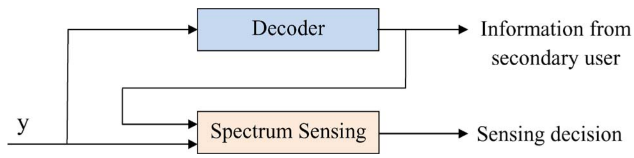

Fig. 3. Receiver structure of the proposed cognitive radio system.

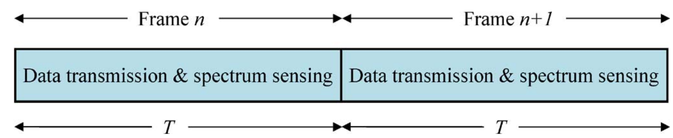

Fig. 4. Frame structure of the proposed cognitive radio system.

the secondary transmitter is cancelled out from the aggregate received signal y and the remaining signal

$$\tilde{y} = \theta x_p + n \tag{2}$$

is used to perform spectrum sensing. As a result, instead of using a limited amount of time τ (as in the frame structure of Fig. 1), almost the whole duration of the frame T can be used for spectrum sensing under the proposed cognitive radio system.[3] This way, we are able to perform spectrum sensing and data transmission at the same time and therefore maximize the duration of both.

C. Frame Structure

The frame structure of the proposed cognitive radio system is presented in Fig. 4 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 times are simultaneously maximized. The significance of this result is twofold. First, under perfect cancellation, the increased sensing time

I) enables the detection of very weak signals from the primary users, the detection of which under the frame structure of Fig. 1 would significantly reduce the data transmission time, hence the throughput of the cognitive radio system;

II) leads to an improved detection probability, thus better protection of the primary users from harmful interference, and a decreased false alarm probability, which enables a better use of the available unused spectrum, considering the fact that a false alarm prevents the secondary users from accessing an idle frequency band using higher transmit power, and therefore limits their achievable throughput;

III) facilitates the use of more complex spectrum sensing techniques that exhibit increased spectrum sensing capabilities, but require higher sensing time (such as cyclostationary detection [14], Generalized Likelihood Ratio Test (GLRT)-based [15] or covariance-based [16] spectrum sensing techniques), which prohibits their application for quick periodical spectrum sensing under the frame structure of Fig. 1;

IV) the calculation of the optimal sensing time is no longer an issue and does not need to be adapted or transmitted back to the secondary users;

V) continuous spectrum sensing can be achieved under the proposed cognitive radio system, which ensures better protection of the primary networks.

Finally, the second important aspect is that the sensing time slot τ of the frame structure of Fig. 1 is now used for data transmission, which leads to an increase in the achievable throughput of the cognitive radio system on the one hand, and facilitates the continuity of data transmission on the other.

III. Ergodic Capacity of the Proposed Spectrum Sharing Scheme

In this section, we study the problem of deriving the optimal power allocation strategy that maximizes the ergodic capacity of a cognitive radio network that operates under the proposed spectrum sharing scheme. In the proposed cognitive radio system, the secondary users adapt their transmit power at the end of each frame based on the decision of spectrum sensing, and transmit using higher power P_0 when the frequency band is detected to be idle and lower power P_1 when it is detected to be active. Following the approach of [6], [12], [17], the instantaneous transmission rates when the frequency band is idle (H_0) and active (H_1) are given by

$$r_0 = \log_2\left(1 + \frac{gP_0}{\sigma_n^2}\right), \quad r_1 = \log_2\left(1 + \frac{gP_1}{\sigma_n^2 + \sigma_p^2}\right) \tag{3}$$

respectively, where σ_p^2 denotes the received power from the primary users. The latter parameter restricts the achievable throughput of all spectrum sharing cognitive radio networks and indicates the importance of spectrum sensing and optimal power allocation on the throughput maximization of spectrum sharing cognitive radio networks. However, considering the fact that perfect spectrum sensing may not be achievable in practice, we consider the more realistic scenario of imperfect spectrum sensing, where the actual status of the primary users might be falsely detected. Therefore, we can distinguish four different cases of instantaneous transmission rates based on the actual status of the primary users (active/idle) and the decision of the secondary users (primary user present/absent) as follows:

$$r_{00} = \log_2\left(1 + \frac{gP_0}{\sigma_n^2}\right), \quad r_{01} = \log_2\left(1 + \frac{gP_1}{\sigma_n^2}\right)$$
$$r_{10} = \log_2\left(1 + \frac{gP_0}{\sigma_n^2 + \sigma_p^2}\right), \quad r_{11} = \log_2\left(1 + \frac{gP_1}{\sigma_n^2 + \sigma_p^2}\right).$$

Here, the first index number of the instantaneous transmission rates indicates the actual status of the primary users ("0" for

[3]The actual sensing time is equal to the frame duration T minus the required time τ_f for the spectrum sensing decision of the secondary receiver to reach the secondary transmitter.

idle, "1" for active) and the second index number, the decision made by the secondary users ("0" for absent, "1" for present).

In order to keep the long-term power budget and effectively protect the primary users from harmful interference, we consider an average (over all fading states) transmit and interference power constraint that can be formulated as follows:

$$\mathbb{E}_{g,h}\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0+\mathcal{P}(H_0)\mathcal{P}_{fa}P_1+\mathcal{P}(H_1)\cdot(1-\mathcal{P}_d)P_0+\mathcal{P}(H_1)\mathcal{P}_dP_1\}\le P_{av} \quad (4)$$

$$\mathbb{E}_{g,h}\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0+\mathcal{P}(H_1)\mathcal{P}_dhP_1\}\le\Gamma \quad (5)$$

where $\mathcal{P}(H_0)$ and $\mathcal{P}(H_1)$ denote the probability that the frequency band is idle and active, respectively, $\mathcal{P}_d$ and $\mathcal{P}_{fa}$ represent the detection and false alarm probability, respectively, whereas P_{av} denotes the maximum average transmit power of the secondary users, and Γ the maximum average interference power that is tolerable by the primary users. The reason for choosing an average interference power constraint is based on the results in [13] and [18], which indicate that an average interference power constraint leads to higher ergodic throughput for the cognitive radio system, and provides better protection for the primary users compared to a peak interference power constraint.

Finally, the optimization problem that maximizes the ergodic throughput of the proposed spectrum sharing cognitive radio system under joint average transmit and interference power constraints can be formulated as follows:

$$\begin{aligned}\underset{\{P_0,P_1\}}{\text{maximize}}\quad & C=\mathbb{E}_{g,h}\{\mathcal{P}(H_1)\mathcal{P}_dr_{11}+\mathcal{P}(H_0)\mathcal{P}_{fa}r_{01}\\ &+\mathcal{P}(H_1)(1-\mathcal{P}_d)r_{10}\\ &+\mathcal{P}(H_0)(1-\mathcal{P}_{fa})r_{00}\}\\ \text{subject to}\quad & (4),(5),\quad P_0\ge0,\quad P_1\ge0. \end{aligned} \quad (6)$$

The Lagrangian with respect to the transmit powers P_0 and P_1 is given by

$$\begin{aligned}&L(P_0,P_1,\lambda,\mu)\\ &=\mathbb{E}_{g,h}\{\mathcal{P}(H_1)\mathcal{P}_dr_{11}+\mathcal{P}(H_0)\mathcal{P}_{fa}r_{01}\\ &\quad+\mathcal{P}(H_1)(1-\mathcal{P}_d)r_{10}+\mathcal{P}(H_0)(1-\mathcal{P}_{fa})r_{00}\}\\ &\quad-\lambda\mathbb{E}_{g,h}\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0+\mathcal{P}(H_0)\mathcal{P}_{fa}P_1\\ &\quad+\mathcal{P}(H_1)(1-\mathcal{P}_d)P_0+\mathcal{P}(H_1)\mathcal{P}_dP_1\}+\lambda P_{av}\\ &\quad-\mu\mathbb{E}_{g,h}\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0+\mathcal{P}(H_1)\mathcal{P}_dhP_1\}+\mu\Gamma\end{aligned} \quad (7)$$

whereas the dual function can be obtained by

$$d(\lambda,\mu)=\sup_{P_0,P_1}L(P_0,P_1,\lambda,\mu). \quad (8)$$

In order to calculate the dual function $d(\lambda,\mu)$, the supremum of the Lagrangian with respect to the transmit powers P_0 and P_1 needs to be obtained. We therefore apply the primal-dual decomposition method [19], which facilitates the solution of the joint optimization problem by decomposing it into two convex single-variable optimization problems, one for each of the transmit powers P_0 and P_1, as follows:

Subproblem 1:

$$\begin{aligned}&\underset{\{P_0\ge0\}}{\text{maximize}}\\ &f_1(P_0)=\mathbb{E}_{g,h}\left\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})\log_2\left(1+\frac{gP_0}{\sigma_n^2}\right)\right.\\ &\qquad\left.+\mathcal{P}(H_1)(1-\mathcal{P}_d)\log_2\left(1+\frac{gP_0}{\sigma_n^2+\sigma_p^2}\right)\right\}\\ &\qquad-\lambda\mathbb{E}_{g,h}\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0+\mathcal{P}(H_1)(1-\mathcal{P}_d)P_0\}\\ &\qquad-\mu\mathbb{E}_{g,h}\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0\}.\end{aligned} \quad (9)$$

Subproblem 2:

$$\begin{aligned}&\underset{\{P_1\ge0\}}{\text{maximize}}\\ &f_2(P_1)=\mathbb{E}_{g,h}\left\{\mathcal{P}(H_0)\mathcal{P}_{fa}\log_2\left(1+\frac{gP_1}{\sigma_n^2}\right)\right.\\ &\qquad\left.+\mathcal{P}(H_1)\mathcal{P}_d\log_2\left(1+\frac{gP_1}{\sigma_n^2+\sigma_p^2}\right)\right\}\\ &\qquad-\lambda\mathbb{E}_{g,h}\{\mathcal{P}(H_0)\mathcal{P}_{fa}P_1+\mathcal{P}(H_1)\mathcal{P}_dP_1\}\\ &\qquad-\mu\mathbb{E}_{g,h}\{\mathcal{P}(H_1)\mathcal{P}_dhP_1\}.\end{aligned} \quad (10)$$

After forming their Lagrangian functions and applying the Karush–Kuhn–Tucker (KKT) conditions, the optimal powers P_0 and P_1 for given λ, μ are given by

$$P_0=\left[\frac{A_0+\sqrt{\Delta_0}}{2}\right]^+,\quad P_1=\left[\frac{A_1+\sqrt{\Delta_1}}{2}\right]^+ \quad (11)$$

where $[x]^+$ denotes $\max(0,x)$

$$A_0=\frac{\log_2(e)(\alpha_0+\beta_0)}{\lambda(\alpha_0+\beta_0)+\mu\beta_0h}-\frac{2\sigma_n^2+\sigma_p^2}{g} \quad (12)$$

$$\Delta_0=A_0^2-\frac{4}{g}\left\{\frac{\sigma_n^2+\sigma_p^2}{g\sigma_n^{-2}}-\frac{\log_2(e)\left[\alpha_0(\sigma_n^2+\sigma_p^2)+\beta_0\sigma_n^2\right]}{\lambda(\alpha_0+\beta_0)+\mu\beta_0h}\right\} \quad (13)$$

$$A_1=\frac{\log_2(e)(\alpha_1+\beta_1)}{\lambda(\alpha_1+\beta_1)+\mu\beta_1h}-\frac{2\sigma_n^2+\sigma_p^2}{g} \quad (14)$$

$$\Delta_1=A_1^2-\frac{4}{g}\left\{\frac{\sigma_n^2+\sigma_p^2}{g\sigma_n^{-2}}-\frac{\log_2(e)\left[\alpha_1(\sigma_n^2+\sigma_p^2)+\beta_1\sigma_n^2\right]}{\lambda(\alpha_1+\beta_1)+\mu\beta_1h}\right\} \quad (15)$$

and the parameters α_0, β_0, α_1, β_1 in (12)–(15) are given by $\alpha_0=\mathcal{P}(H_0)(1-\mathcal{P}_{fa})$, $\beta_0=\mathcal{P}(H_1)(1-\mathcal{P}_d)$, $\alpha_1=\mathcal{P}(H_0)\mathcal{P}_{fa}$ and $\beta_1=\mathcal{P}(H_1)\mathcal{P}_d$, respectively.

In order to determine the optimal power allocation strategy, the optimal values of the Lagrangian multipliers λ and μ that minimize the dual function $d(\lambda,\mu)$ need to be found. The ellipsoid method [20] is used here to find the optimal solution, which requires the subgradient of the dual function $d(\lambda,\mu)$. The latter is given by the following proposition.

Proposition 1: The subgradient of the dual function $d(\lambda,\mu)$ is $[D,E]$, where D is given by $D=P_{av}-\mathbb{E}_{g,h}\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0+\mathcal{P}(H_0)\mathcal{P}_{fa}P_1+\mathcal{P}(H_1)(1-\mathcal{P}_d)P_0+\mathcal{P}(H_1)\mathcal{P}_dP_1\}$, E is given by $E=\Gamma-\mathbb{E}_{g,h}\{\mathcal{P}(H_1)(1-$

$\mathcal{P}_d)hP_0 + \mathcal{P}(H_1)\mathcal{P}_d hP_1\}$, where $\lambda \geq 0$, $\mu \geq 0$, and P_0 and P_1 denote the optimal power allocation in (8) for fixed λ, μ.

Proof: See Appendix A. ■

The algorithm that acquires the optimal power allocation strategy that maximizes the ergodic capacity of the proposed spectrum sharing cognitive radio system is presented in the following table.

Algorithm 1: Optimal power allocation that maximizes the ergodic capacity of the proposed spectrum sharing cognitive radio system.

► Initialize λ, μ.
► Repeat:

- calculate P_0, P_1 using (11)–(15);
- update λ, μ using the ellipsoid method;

► Until λ, μ converge.

IV. Outage Capacity of the Proposed Spectrum Sharing Scheme

The ergodic capacity studied in the previous section is an effective metric for fast fading channels or delay-insensitive applications [21], where a block of information can experience all different fading states of the channel during transmission, whereas for slow fading channels or delay-sensitive applications, such as voice and video transmission, the outage capacity [21], [22] comprises a more appropriate metric for the capacity of the system due to the fact that only a cross section of the channel characteristics is experienced during the transmission period of a block of information. The outage capacity C_{out} is defined as the highest transmission rate that can be achieved by the communications system, while keeping the probability of outage under a maximum value.

In this section, we study the outage capacity of the proposed spectrum sharing cognitive radio system, and derive the power allocation strategy for a combination of different constraints on the outage capacity that include average transmit power constraints, average interference power constraints and peak interference power constraints. More specifically, we will consider, as in [11], the truncated channel inversion with fixed rate (TIFR) technique, where the secondary transmitter uses the channel side information (CSI) to invert the channel fading, in order to achieve a constant signal-to-noise ratio (SNR) at the secondary receiver during the periods when the channels fade above a certain "cutoff" value [23]. This adaptive transmission scheme offers the advantage of non-zero achievable rates for a target outage probability $\mathcal{P}_{out} = \bar{\mathcal{P}}_{out}$, even when the fading is extremely severe such as in Rayleigh fading cases, where a constant transmission rate cannot be achieved under all fading states of the channel.

In the following, we distinguish four different cases based on the aforementioned constraints on the capacity, and derive the capacity under the TIFR transmission policy, as well as the outage capacity of the proposed spectrum sharing cognitive radio system under Rayleigh fading channels.

A. *Outage Capacity Under Average Transmit and Interference Power Constraints*

We consider here the capacity of the proposed spectrum sharing cognitive radio system under two constraints, namely under an average transmit power constraint and an average interference power constraint, the same as in the previous section for the ergodic capacity. These can be formulated as follows:

$$\mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0 + \mathcal{P}(H_1)\mathcal{P}_d hP_1\right\} \leq \Gamma \tag{16}$$

$$\begin{aligned}\mathbb{E}_{g,h}\{&\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0 + \mathcal{P}(H_0)\mathcal{P}_{fa}P_1 \\ &+ \mathcal{P}(H_1)(1-\mathcal{P}_d)P_0 + \mathcal{P}(H_1)\mathcal{P}_d P_1\} \leq P_{av}.\end{aligned} \tag{17}$$

As mentioned in the beginning of this section, in the TIFR technique the secondary transmitter inverts the channel fading, in order to achieve a constant rate at the secondary receiver when the channel fading is higher than a "cutoff" threshold. We define here this cutoff threshold by γ_0 when the primary users are detected to be idle and by γ_1 when the primary users are detected to be active. The respective transmit powers of the secondary user are given by

$$P_0(g,h) = \begin{cases} \frac{\alpha}{g}, & \frac{h}{g} \leq \frac{\gamma_0}{\sigma^2} \\ 0, & \frac{h}{g} > \frac{\gamma_0}{\sigma^2} \end{cases} \tag{18}$$

$$P_1(g,h) = \begin{cases} \frac{\alpha}{g}, & \frac{h}{g} \leq \frac{\gamma_1}{\sigma^2} \\ 0, & \frac{h}{g} > \frac{\gamma_1}{\sigma^2} \end{cases} \tag{19}$$

where the parameters γ_0, γ_1, and α must be found so that the average interference power constraint (16) and the average transmit power constraint (17) are met. The transmit power in both cases is suspended (as in [11]) when the link g between the secondary transmitter and the respective receiver is weak compared to the interference channel h from the secondary transmitter to the primary receiver. We consider here the same metric, i.e. h/g, for the case that the primary users are detected to be idle, namely for $P_0(g,h)$, in order to take into consideration the realistic scenario of imperfect spectrum sensing, so that to effectively protect the primary users from harmful interference when a miss-detection occurs.

Based on the average interference power constraint (16), the average transmit power constraint (17) and the Appendices B1 and B2, the parameter α should satisfy the following constraints:

$$\begin{aligned}\alpha =& \Gamma \cdot \left\{\mathcal{P}(H_1)(1-\mathcal{P}_d)\left[\log\left(1+\frac{\gamma_0}{\sigma^2}\right) - \frac{\gamma_0}{\gamma_0+\sigma^2}\right]\right. \\ &\left. + \mathcal{P}(H_1)\mathcal{P}_d\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1+\sigma^2}\right]\right\}^{-1} \\ =& t_1(\gamma_0,\gamma_1)\end{aligned} \tag{20}$$

$$\alpha \le \frac{P_{av}}{K_0 \log\left(1+\frac{\gamma_0}{\sigma^2}\right) + K_1 \log\left(1+\frac{\gamma_1}{\sigma^2}\right)} = t_2(\gamma_0, \gamma_1) \tag{21}$$

where the parameters K_0 and K_1 are given by

$$K_0 = \mathcal{P}(H_0)(1-\mathcal{P}_{fa}) + \mathcal{P}(H_1)(1-\mathcal{P}_d) \tag{22}$$

$$K_1 = \mathcal{P}(H_0)\mathcal{P}_{fa} + \mathcal{P}(H_1)\mathcal{P}_d \tag{23}$$

respectively.

Furthermore, the outage probability of the proposed cognitive radio system under average transmit and interference power constraints is proven in Appendix B3 to be given by $\mathcal{P}_{out} = K_0\sigma^2/(\gamma_0+\sigma^2) + K_1\sigma^2/(\gamma_1+\sigma^2)$. Therefore, the channel capacity under the TIFR policy can be obtained as follows:

$$C_{TIFR} = \max_{\gamma_0,\gamma_1}\left\{\log\left(1+\frac{1}{\sigma^2}\min\{t_1(\gamma_0,\gamma_1), t_2(\gamma_0,\gamma_1)\}\right) \cdot \left(1-\frac{K_0\sigma^2}{\gamma_0+\sigma^2}-\frac{K_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \tag{24}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0 and γ_1.

On the other hand, the outage capacity requires that a target outage probability is met, namely $\mathcal{P}_{out} = \bar{\mathcal{P}}_{out}$. As a result, the parameters t_1 and t_2 from (20) and (21) take the following form:

$$\bar{t}_1(\gamma_0) = \frac{\Gamma}{\mathcal{P}(H_1)}\left\{\frac{\log\left(1+\frac{\gamma_0}{\sigma^2}\right)-\frac{\gamma_0}{\gamma_0+\sigma^2}}{(1-\mathcal{P}_d)^{-1}} + \mathcal{P}_d\left[\frac{\bar{\mathcal{P}}_{out}}{K_1} + \log\left(\frac{K_1}{\bar{\mathcal{P}}_{out}-\frac{K_0\sigma^2}{\gamma_0+\sigma^2}}\right) - \frac{K_0\sigma^2}{K_1(\gamma_0+\sigma^2)} - 1\right]\right\}^{-1} \tag{25}$$

$$\bar{t}_2(\gamma_0) = P_{av}\left[K_0\log\left(1+\frac{\gamma_0}{\sigma^2}\right) + K_1\log(K_1) - K_1\log\left(\bar{\mathcal{P}}_{out}-\frac{K_0\sigma^2}{\gamma_0+\sigma^2}\right)\right]^{-1} \tag{26}$$

respectively. Finally, the outage capacity of the proposed spectrum sharing cognitive radio system under joint average transmit and interference power constraints, for a target outage probability $\bar{\mathcal{P}}_{out}$, is given by

$$C_{out} = \max_{\gamma_0}\left\{\log\left(1+\frac{1}{\sigma^2}\min\{\bar{t}_1(\gamma_0), \bar{t}_2(\gamma_0)\}\right)\cdot(1-\bar{\mathcal{P}}_{out})\right\} \tag{27}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0.

B. Outage Capacity Under Both Average and Peak Interference Power Constraints

In this subsection, we consider the TIFR and outage capacity of the proposed spectrum sharing cognitive radio system under joint average and peak interference power constraints, as in [11]. The aforementioned constraints can be formulated as follows:

$$\mathbb{E}_{g,h}\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0(g,h) + \mathcal{P}(H_1)\mathcal{P}_d hP_1(g,h)\} \le \Gamma \tag{28}$$

$$\mathcal{P}(H_1)(1-\mathcal{P}_d)P_0(g,h)h \le Q_{peak} \tag{29}$$

$$\mathcal{P}(H_1)\mathcal{P}_d P_1(g,h)h \le Q_{peak} \tag{30}$$

where we have taken into consideration the interference caused under both cases, namely when the frequency band is correctly detected to be active and falsely detected to be idle. The transmit power for each case under the channel inversion technique is given by (18) and (19).

Based on the average interference power constraint (28), the peak interference power constraints (29) and (30) and Appendix B1, the parameter α should satisfy the following constraints:

$$\alpha = \frac{\Gamma}{\mathcal{P}(H_1)}\left\{(1-\mathcal{P}_d)\left[\log\left(1+\frac{\gamma_0}{\sigma^2}\right)-\frac{\gamma_0}{\gamma_0+\sigma^2}\right] + \mathcal{P}_d\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right)-\frac{\gamma_1}{\gamma_1+\sigma^2}\right]\right\}^{-1} = q_1(\gamma_0,\gamma_1) \tag{31}$$

$$\alpha \le \frac{Q_{peak}\sigma^2}{\mathcal{P}(H_1)(1-\mathcal{P}_d)\gamma_0} = q_2(\gamma_0) \tag{32}$$

$$\alpha \le \frac{Q_{peak}\sigma^2}{\mathcal{P}(H_1)\mathcal{P}_d\gamma_1} = q_3(\gamma_1). \tag{33}$$

The outage probability under the imposed constraints is given in Appendix B3. Therefore, the maximum capacity under the TIFR transmission policy can be obtained as follows:

$$C_{TIFR} = \max_{\gamma_0,\gamma_1}\left\{\log\left(1+\frac{\min\{q_1(\gamma_0,\gamma_1), q_2(\gamma_0), q_3(\gamma_1)\}}{\sigma^2}\right) \cdot \left(1-\frac{K_0\sigma^2}{\gamma_0+\sigma^2}-\frac{K_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \tag{34}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0 and γ_1. Finally, for a target outage probability $\mathcal{P}_{out} = \bar{\mathcal{P}}_{out}$, the threshold γ_1 can be written as a function of γ_0 as $\bar{\gamma}_1(\gamma_0) = K_1\sigma^2/(\bar{\mathcal{P}}_{out} - K_0\sigma^2/(\gamma_0+\sigma^2)) - \sigma^2$. Therefore the outage capacity is given by

$$C_{out} = \max_{\gamma_0}\left\{\log\left(1+\frac{\min\{q_1(\gamma_0), q_2(\gamma_0), q_3(\gamma_0)\}}{\sigma^2}\right) \cdot (1-\bar{\mathcal{P}}_{out})\right\} \tag{35}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0.

C. Outage Capacity Under Average Transmit and Interference Power Constraints With High Target Detection Probability

We consider now the case that a high target detection probability $\mathcal{P}_d = \bar{\mathcal{P}}_d$ is employed on the proposed spectrum sharing cognitive radio system, and that when the primary users are detected to be idle, the secondary transmitter accesses the frequency band in an opportunistic spectrum access manner, namely it does not impose an interference power constraint. In this case, the average transmit and interference power constraint take the following form:

$$\mathbb{E}_{g,h}\{\bar{K}_0 P_0 + \bar{K}_1 P_1\} \leq P_{av} \tag{36}$$
$$\mathbb{E}_{g,h}\{\mathcal{P}(H_1)\bar{\mathcal{P}}_d h P_1\} \leq \Gamma \tag{37}$$

respectively, where $\bar{K}_0$ and $\bar{K}_1$ are given by (22) and (23) for $\mathcal{P}_d = \bar{\mathcal{P}}_d$. The transmit power of the secondary user under the TIFR policy is now given by

$$P_0(g) = \begin{cases} \frac{\alpha}{g}, & g > \frac{\gamma_0}{\sigma^2} \\ 0, & g \leq \frac{\gamma_0}{\sigma^2} \end{cases} \tag{38}$$
$$P_1(g,h) = \begin{cases} \frac{\alpha}{g}, & \frac{h}{g} \leq \frac{\gamma_1}{\sigma^2} \\ 0, & \frac{h}{g} > \frac{\gamma_1}{\sigma^2} \end{cases} \tag{39}$$

where it can be seen that the transmit power P_0 (when the primary users are detected to be idle) depends only on the channel g between the secondary transmitter and the respective receiver, and is independent of the interference channel h to the primary receiver.

Based on the average transmit power constraint (36), the average interference power constraint (37), and the Appendices B4 and B5, the parameter α should satisfy the following constraints

$$\alpha = \frac{\Gamma}{\mathcal{P}(H_1)\bar{\mathcal{P}}_d\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1+\sigma^2}\right]} = u_1(\gamma_1) \tag{40}$$
$$\alpha \leq \frac{P_{av}}{\bar{K}_0 \mathrm{E}_1\left(\frac{\gamma_0}{\sigma^2}\right) + \bar{K}_1 \log\left(1+\frac{\gamma_1}{\sigma^2}\right)} = u_2(\gamma_0,\gamma_1) \tag{41}$$

where $E_1(\cdot)$ denotes the exponential integral of order 1 [24].

The outage probability is proven in Appendix B6 to be given by $\mathcal{P}_{out} = \bar{K}_0 - \bar{K}_0 \exp(-\gamma_0/\sigma^2) + \bar{K}_1\sigma^2/(\gamma_1+\sigma^2)$. As a result, the maximum capacity under the TIFR transmission policy is given by

$$C_{TIFR} = \max_{\gamma_0,\gamma_1}\left\{\log\left(1+\frac{\min\{u_1(\gamma_1), u_2(\gamma_0,\gamma_1)\}}{\sigma^2}\right) \cdot\left(1-\bar{K}_0+\bar{K}_0\exp\left(-\frac{\gamma_0}{\sigma^2}\right)-\frac{\bar{K}_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \tag{42}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0 and γ_1.

For a target outage probability $\mathcal{P}_{out} = \bar{\mathcal{P}}_{out}$, the cutoff value γ_1 can be written as a function of γ_0 as $\gamma_1(\gamma_0) = \bar{K}_1\sigma^2/(\bar{\mathcal{P}}_{out} - \bar{K}_0 + \bar{K}_0\exp(-\gamma_0/\sigma^2)) - \sigma^2$, and therefore, the outage capacity is finally given by:

$$C_{out} = \max_{\gamma_0}\left\{\log\left(1+\frac{\min\{\bar{u}_1(\gamma_0), \bar{u}_2(\gamma_0)\}}{\sigma^2}\right)(1-\bar{\mathcal{P}}_{out})\right\} \tag{43}$$

where the maximum can be obtained by searching numerically for the optimal value of γ_0. The expressions for $\bar{u}_1(\gamma_0)$ and $\bar{u}_2(\gamma_0)$ can be easily found from (40) and (41) by replacing $\gamma_1(\gamma_0)$ from the equation above.

D. Outage Capacity Under Both Average and Peak Interference Power Constraints With High Target Detection Probability

In this last subsection, we consider a similar scenario to one in the previous subsection, only this time under joint average and peak interference power constraints on the secondary transmitter. The aforementioned constraints can be expressed as follows:

$$\mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)\bar{\mathcal{P}}_d h P_1(g,h)\right\} \leq \Gamma \tag{44}$$
$$\mathcal{P}(H_1)\bar{\mathcal{P}}_d P_1(g,h) h \leq Q_{peak}. \tag{45}$$

The power allocation for this case is given by (38) and (39). Based on the constraints (44) and (45), and Appendix B5, the parameter α should satisfy the following constraints:

$$\alpha = \frac{\Gamma}{\mathcal{P}(H_1)\bar{\mathcal{P}}_d\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1+\sigma^2}\right]} = w_1(\gamma_1) \tag{46}$$
$$\alpha \leq \frac{Q_{peak}\sigma^2}{\mathcal{P}(H_1)\bar{\mathcal{P}}_d\gamma_1} = w_2(\gamma_1). \tag{47}$$

The outage probability is proven in Appendix B6 to be equal to $\mathcal{P}_{out} = \bar{K}_0 - \bar{K}_0\exp(-\gamma_0/\sigma^2) + \bar{K}_1\sigma^2/(\gamma_1+\sigma^2)$. Therefore, the maximum capacity under the TIFR transmission policy for this case is given by

$$\begin{aligned} C_{TIFR} &= \max_{\gamma_0,\gamma_1}\left\{\log\left(1+\frac{\min\{w_1(\gamma_1), w_2(\gamma_1)\}}{\sigma^2}\right)\right. \\ &\qquad \left.\cdot\left(1-\bar{K}_0+\bar{K}_0\exp\left(-\frac{\gamma_0}{\sigma^2}\right)-\frac{\bar{K}_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\} \\ &= \max_{\gamma_1}\left\{\log\left(1+\frac{1}{\sigma^2}\min\{w_1(\gamma_1), w_2(\gamma_1)\}\right)\right. \\ &\qquad \left.\cdot\left(1-\frac{\bar{K}_1\sigma^2}{\gamma_1+\sigma^2}\right)\right\}. \end{aligned} \tag{48}$$

However, it can be seen from (46)–(48) that $\lim_{\gamma_1\to 0} C_{TIFR} = +\infty$. This result can be easily explained by the fact that the secondary user under the imposed constraints can transmit using infinite power; as seen from (46) and (47), for $\gamma_1 \to 0$, we have $\alpha \leq +\infty$. This is clearly an unrealistic scenario that did not occur in the scenario of subsection B or in [11] due to the interference constraint imposed on the transmit power for the case of miss-detection. For this reason, we choose to apply an (additional) average transmit power constraint that according to Appendix B4 can be formulated as follows:

$$\mathbb{E}_{g,h}\{\bar{K}_0 P_0 + \bar{K}_1 P_1\} \leq P_{av}$$
$$\Rightarrow \alpha \leq \frac{P_{av}}{\bar{K}_0\mathrm{E}_1\left(\frac{\gamma_0}{\sigma^2}\right) + \bar{K}_1\log\left(1+\frac{\gamma_1}{\sigma^2}\right)} = w_3(\gamma_0,\gamma_1). \tag{49}$$

The maximum capacity under the TIFR transmission policy is now given by

$$C_{TIFR} = \max_{\gamma_0,\gamma_1} \Bigg\{ (1 - \mathcal{P}_{out}(\gamma_0,\gamma_1)) \cdot \log\left(1 + \frac{\min\{w_1(\gamma_1), w_2(\gamma_1), w_3(\gamma_0,\gamma_1)\}}{\sigma^2}\right) \Bigg\} \quad (50)$$

and the respective outage capacity for a target probability of outage $\bar{\mathcal{P}}_{out}$ by

$$C_{out} = \max_{\gamma_0} \Bigg\{ \log\left(1 + \frac{\min\{\bar{w}_1(\gamma_0), \bar{w}_2(\gamma_0), \bar{w}_3(\gamma_0)\}}{\sigma^2}\right) \cdot (1 - \bar{\mathcal{P}}_{out}) \Bigg\} \quad (51)$$

where $\bar{w}_1(\gamma_0)$, $\bar{w}_2(\gamma_0)$ and $\bar{w}_3(\gamma_0)$ can be found from (46), (47) and (49), for $\gamma_1 = \bar{K}_1\sigma^2/(\bar{\mathcal{P}}_{out} - \bar{K}_0 + \bar{K}_0 \exp(-\gamma_0/\sigma^2)) - \sigma^2$.

V. Simulation Results

In this section, we present simulation results for the proposed cognitive radio system and compare it with the conventional spectrum sharing scheme. We adopt the energy detector [10] as a method of spectrum sensing, although any spectrum sensing technique [14]–[16], [25] can be used under the proposed cognitive radio system. The detection and false alarm probability of the energy detector are given by $\mathcal{P}_d^{ED} = \mathcal{Q}((\epsilon/\sigma^2 - \psi - 1)\sqrt{\tau f_s/(2\psi+1)})$ and $\mathcal{P}_{fa}^{ED} = \mathcal{Q}((\epsilon/\sigma^2 - 1)\sqrt{\tau f_s})$, where $\mathcal{Q}(x) = 1/\sqrt{2\pi}\int_x^\infty \exp(-t^2/2)dt$, τ is the sensing time, ϵ the decision threshold, ψ the received SNR from the primary user and f_s the sampling frequency. We consider Rayleigh fading channels, $T = 100$ ms, $f_s = 6$ MHz, $\mathcal{P}(H_0) = 0.6$, $\sigma^2 = 1$, target detection probability $\mathcal{P}_d = 0.9$ and $\psi = -20$ dB.

A. Ergodic Capacity of the Proposed Spectrum Sharing Scheme

We consider here the ergodic capacity of the proposed cognitive radio system, as studied in Section III. As in [13], the channels g and h are considered to be the squared norms of independent circularly symmetric complex Gaussian (CSCG) random variables that are distributed as $\mathcal{CN}(0,1)$ and $\mathcal{CN}(0,10)$, respectively. The maximum average tolerable interference power at the primary receiver is considered to be $\Gamma = 1$, whereas an additional channel power gain attenuation is considered for the channel h between the secondary transmitter (SU-Tx) and the primary receiver (PU-Rx), where an attenuation of 10 dB, for example, means that $\mathbb{E}\{h\} = 1$.

In Fig. 5, the ergodic throughput of the proposed and the conventional spectrum sharing scheme are presented versus the additional channel power gain attenuation between the secondary transmitter and the primary receiver for different values of the average transmit power P_{av} of the secondary users. It can be clearly seen from Fig. 5 that the ergodic throughput of the proposed cognitive radio system is significantly higher compared to the conventional spectrum sharing system, even for very low values of the channel power gain attenuation between the SU-Tx and the PR-Rx. On the other hand, the ergodic throughput of the conventional spectrum sharing scheme reaches the respective of the proposed cognitive radio system only when the average interference power constraint no longer restricts the transmit power of the secondary users, hence the ergodic throughput of the cognitive radio system, which is therefore only restricted by the average transmit power constraint.

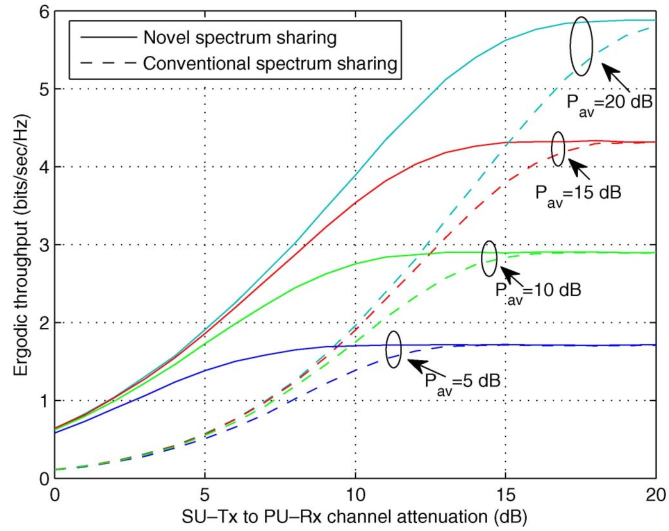

Fig. 5. Ergodic throughput of the proposed and the conventional spectrum sharing cognitive radio system versus the additional channel power gain attenuation.

In Fig. 6, the ergodic throughput of the proposed cognitive radio system is presented versus the additional channel power gain attenuation between the secondary transmitter and the primary receiver for different values of target detection probability and average transmit power of the secondary users. It can be easily observed from Fig. 6 that the ergodic throughput of the proposed cognitive radio system increases as the target detection probability receives higher values. This interesting result can be explained by the fact that as the target detection probability $\mathcal{P}_d$ increases, the probability of missed detection $\mathcal{P}_{md} = 1 - \mathcal{P}_d$ decreases, and therefore the restriction on the transmit power P_0 imposed by the average interference power constraint (5), when the primary users are detected to be idle, reduces. Hence, the secondary users under higher values of target detection probability $\mathcal{P}_d$ can communicate using higher transmit power during the periods that the primary users are detected to be idle and as a result, the ergodic throughput of the cognitive radio system increases. The ergodic throughput of the conventional spectrum sharing scheme is omitted in Fig. 6, because it is independent of the detection probability. However, it can be seen from Figs. 5 and 6 that the ergodic throughput of the proposed cognitive radio system under increased probability of detection is significantly greater compared to the conventional spectrum sharing scheme.

Finally, the ergodic throughput versus the additional channel power gain attenuation for the conventional sensing-based spectrum sharing scheme of Fig. 1 [8] and the proposed

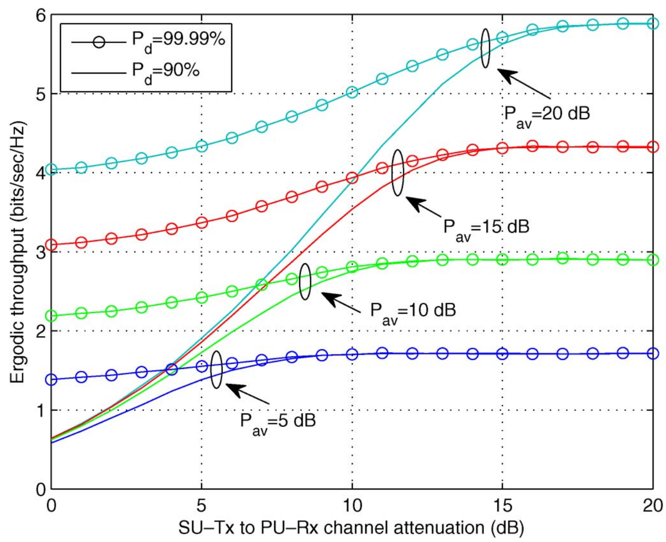

Fig. 6. Ergodic throughput of the proposed spectrum sharing cognitive radio system versus the additional channel power gain attenuation for different values of target detection probability $\mathcal{P}_d$.

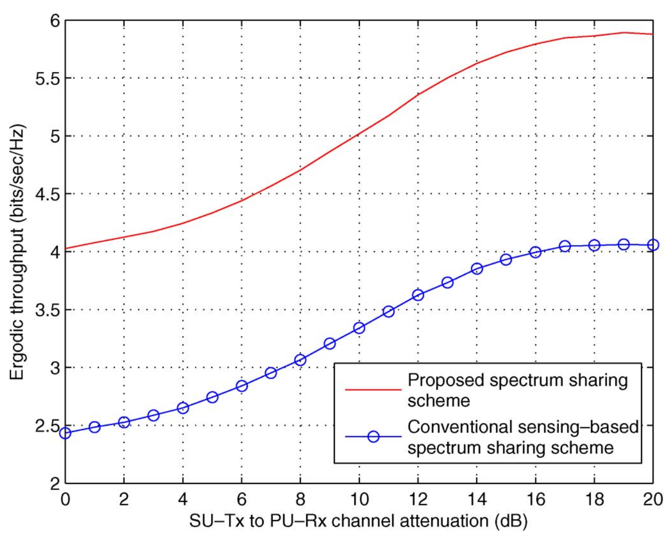

Fig. 7. Ergodic throughput of the proposed spectrum sharing and the conventional sensing-based spectrum sharing scheme versus the additional channel power gain attenuation.

spectrum sharing scheme (under perfect signal cancellation) is presented in Fig. 7, where we consider $\mathcal{P}_d = 99.99\%$ and $P_{av} = 20$ dB. It can be clearly seen from the figure that the ergodic throughput of the proposed cognitive radio system is considerably higher compared to the system that employs the frame structure of Fig. 1, something which can be explained by the increased sensing time that is required by the latter to achieve the target detection probability, the increased probability of false alarm, and finally the reduced data transmission time.

B. Outage Capacity of the Proposed Spectrum Sharing Scheme

We now consider the outage capacity and the capacity under the TIFR transmission policy of the proposed cognitive radio system, as studied in Section IV. The target outage probability

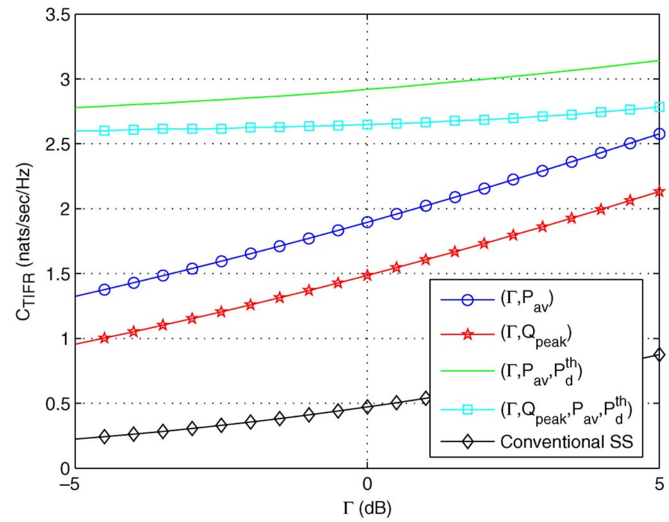

Fig. 8. Maximum capacity under the TIFR transmission policy of the proposed and conventional spectrum sharing (SS) [11] scheme versus the average interference constraint Γ under different constraints.

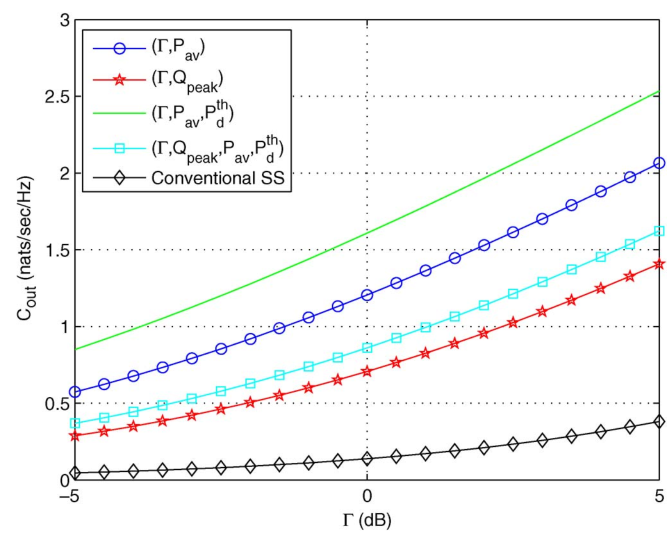

Fig. 9. Outage capacity of the proposed and conventional spectrum sharing (SS) scheme [11] versus the average interference constraint Γ under different constraints and outage probability $\bar{\mathcal{P}}_{out} = 0.1$.

is set to $\bar{\mathcal{P}}_{out} = 0.1$, and the maximum peak interference Q_{peak} is related to the average interference constraint Γ by $\rho = Q_{peak}/\Gamma$, as in [11]. In our simulations, we consider $\rho = 1.5$, $\bar{\mathcal{P}}_d = 0.9$ and $P_{av} = 20$ dB.

In Fig. 8, the maximum capacity of the proposed and the conventional spectrum sharing scheme [11] under the TIFR transmission policy are presented versus the maximum average interference power Γ. The C_{TIFR} capacity of the proposed spectrum sharing scheme is presented for the four cases studied in Section IV. These are distinguished in Figs. 8 and 9 by the applied constraints which are denoted by Γ for the average interference power constraint, P_{av} for the average transmit power constraint, Q_{peak} for the peak interference power constraint, and P_d^{th} for the high target detection probability constraint.

It can be clearly seen from Fig. 8 that the C_{TIFR} capacity of the proposed spectrum sharing scheme is significantly higher compared to the conventional spectrum sharing [11], which can be easily explained by the fact that the secondary users make a more efficient use of the available spectrum by employing a cognitive behavior and obtaining the status (idle/active) of the frequency band, instead of "blindly" assuming that the primary users are always active. The proposed scheme offers an efficient way to perform spectrum sensing and adapt the transmit power based on the spectrum sensing decision, in order to protect the primary users from harmful interference. As expected and seen in Fig. 8, the capacity reduces when a peak interference power constraint is applied, whereas, interestingly, the capacity increases for the case that the opportunistic spectrum access approach is considered when the frequency band is detected to be idle, or (as described in Section IV) a high target detection probability is considered. This approach enables the secondary users to freely access the frequency band when it is detected to be idle and this is what boosts the capacity for the cases under a high target detection probability P_d^{th} seen in Fig. 8.

Finally, the outage capacity is presented in Fig. 9 for the proposed and the conventional spectrum sharing scheme [11]. Similar remarks to the C_{TIFR} capacity can be made for the outage capacity, namely that the outage capacity of the proposed scheme is higher compared to the respective of the conventional spectrum sharing scheme, that a peak interference constraint reduces the achievable outage capacity, and finally, that the adoption of the opportunistic spectrum access approach for the case that the primary users are detected to be idle (what was described as high target detection probability constraint in Sections IV-C and D), leads to a higher achievable outage capacity for the proposed spectrum sharing scheme.

VI. Conclusion

In this paper, we proposed a novel sensing-enhanced spectrum sharing cognitive radio system that significantly improves the ergodic and outage capacity of spectrum sharing cognitive radio networks by performing data transmission and spectrum sensing at the same time. We introduced the receiver and frame structure employed in the proposed cognitive radio system and derived the optimal power allocation strategy that maximizes the ergodic throughput of the proposed cognitive radio system under average transmit and interference power constraints. Furthermore, we studied the outage and TIFR capacity under different combinations of average transmit, average interference and peak interference power constraints. In addition, we provided simulation results, which indicate that the proposed cognitive radio system can considerably improve the ergodic and outage capacity of spectrum sharing cognitive radio networks under perfect secondary signal cancellation. Finally, in our future research we plan to extend this work for multiple primary users and imperfect secondary signal cancellation.

Appendix A
Proof of Proposition 1

Let λ, μ be any feasible values for the $d(\lambda, \mu)$. If we prove that $d(\hat{\lambda}, \hat{\mu}) \geq d(\tilde{\lambda}, \tilde{\mu}) + ([\hat{\lambda}, \hat{\mu}] - [\tilde{\lambda}, \tilde{\mu}])\mathbf{S}^T$ holds for any $\hat{\lambda}$, $\hat{\mu}$, then $\mathbf{S}$ must be a subgradient of $d(\tilde{\lambda}, \tilde{\mu})$ at $\tilde{\lambda}$, $\tilde{\mu}$. We have

$$
\begin{aligned}
&d(\hat{\lambda}, \hat{\mu}) \\
&\quad = \sup_{P_0, P_1} L(P_0, P_1, \hat{\lambda}, \hat{\mu}) \\
&\quad = \mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)\mathcal{P}_d\hat{r}_{11} + \mathcal{P}(H_0)\mathcal{P}_{fa}\hat{r}_{01} + \mathcal{P}(H_1)\right.\\
&\qquad\qquad \left.\cdot(1-\mathcal{P}_d)\hat{r}_{10} + \mathcal{P}(H_0)(1-\mathcal{P}_{fa})\hat{r}_{00}\right\} \\
&\qquad - \hat{\lambda}\mathbb{E}_{g,h}\Big\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})\hat{P}_0 + \mathcal{P}(H_0)\mathcal{P}_{fa}\hat{P}_1 \\
&\qquad\qquad + \mathcal{P}(H_1)(1-\mathcal{P}_d)\hat{P}_0 + \mathcal{P}(H_1)\mathcal{P}_d\hat{P}_1\Big\} + \hat{\lambda}P_{av} \\
&\qquad - \hat{\mu}\mathbb{E}_{g,h}\Big\{\mathcal{P}(H_1)\Big[(1-\mathcal{P}_d)h\hat{P}_0 + \mathcal{P}_d h\hat{P}_1\Big]\Big\} + \hat{\mu}\Gamma \\
&\quad \geq \mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)\mathcal{P}_d\tilde{r}_{11} + \mathcal{P}(H_0)\mathcal{P}_{fa}\tilde{r}_{01} + \mathcal{P}(H_1)\right.\\
&\qquad\qquad \left.\cdot(1-\mathcal{P}_d)\tilde{r}_{10} + \mathcal{P}(H_0)(1-\mathcal{P}_{fa})\tilde{r}_{00}\right\} \\
&\qquad - \hat{\lambda}\mathbb{E}_{g,h}\Big\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})\tilde{P}_0 + \mathcal{P}(H_0)\mathcal{P}_{fa}\tilde{P}_1 \\
&\qquad\qquad + \mathcal{P}(H_1)(1-\mathcal{P}_d)\tilde{P}_0 + \mathcal{P}(H_1)\mathcal{P}_d\tilde{P}_1\Big\} + \hat{\lambda}P_{av} \\
&\qquad - \hat{\mu}\mathbb{E}_{g,h}\Big\{\mathcal{P}(H_1)\Big[(1-\mathcal{P}_d)h\tilde{P}_0 + \mathcal{P}_d h\tilde{P}_1\Big]\Big\} + \hat{\mu}\Gamma \\
&\quad = d(\tilde{\lambda}, \tilde{\mu}) \\
&\qquad + (\hat{\lambda} - \tilde{\lambda})\Bigg(P_{av} - \mathbb{E}_{g,h}\Big\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})\tilde{P}_0 \\
&\qquad\qquad + \mathcal{P}(H_0)\mathcal{P}_{fa}\tilde{P}_1 + \mathcal{P}(H_1)\mathcal{P}_d\tilde{P}_1 \\
&\qquad\qquad + \mathcal{P}(H_1)(1-\mathcal{P}_d)\tilde{P}_0\Big\}\Bigg) \\
&\qquad + (\hat{\mu} - \tilde{\mu})\Bigg(\Gamma - \mathbb{E}_{g,h}\Big\{\mathcal{P}(H_1)(1-\mathcal{P}_d)h\tilde{P}_0 \\
&\qquad\qquad + \mathcal{P}(H_1)\mathcal{P}_d h\tilde{P}_1\Big\}\Bigg)
\end{aligned}
$$

where $\hat{P}_0$ and $\hat{P}_1$ are the optimal solutions when $\lambda = \hat{\lambda}$ and $\mu = \hat{\mu}$, whereas $\tilde{P}_0$ and $\tilde{P}_1$ are the optimal solutions when $\lambda = \tilde{\lambda}$ and $\mu = \tilde{\mu}$. The inequality above results from the fact that $\hat{P}_0$ and $\hat{P}_1$ are the optimal solutions for $\lambda = \hat{\lambda}$ and $\mu = \hat{\mu}$. Thus, the subgradient $\mathbf{S}^T$ is given by $[D, E]$, where D and E are given by

$$
\begin{aligned}
D = P_{av} - \mathbb{E}_{g,h}&\left\{\mathcal{P}(H_0)(1-\mathcal{P}_{fa})P_0 + \mathcal{P}(H_0)\mathcal{P}_{fa}P_1\right.\\
&\left.+\mathcal{P}(H_1)\mathcal{P}_dP_1 + \mathcal{P}(H_1)(1-\mathcal{P}_d)P_0\right\}, \\
E = \Gamma - E_{g,h}&\left\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0 + \mathcal{P}(H_1)\mathcal{P}_d hP_1\right\}.
\end{aligned}
$$

Appendix B
Proof of Analytical Expressions of Section IV

1) Average Interference Power: The average interference power in (16) can be written as follows:

$$
\begin{aligned}
\mathbb{E}_{g,h}&\left\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0 + \mathcal{P}(H_1)\mathcal{P}_d hP_1\right\} \\
&= \iint\limits_{\frac{h}{g}\leq\frac{\gamma_0}{\sigma^2}} \mathcal{P}(H_1)(1-\mathcal{P}_d)\alpha\frac{h}{g}f_h(h)f_g(g)dhdg \\
&\quad + \iint\limits_{\frac{h}{g}\leq\frac{\gamma_1}{\sigma^2}} \mathcal{P}(H_1)\mathcal{P}_d\alpha\frac{h}{g}f_h(h)f_g(g)dhdg. \qquad (52)
\end{aligned}
$$

For Rayleigh fading channels h and g, it can be easily shown that the random variable $u = h/g$ follows a log-logistic distribution given by $f_u(u) = 1/(1+u)^2,\ u \geq 0$ [6]. Thus, (52) can be written as follows:

$$\begin{aligned}
&\mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)(1-\mathcal{P}_d)hP_0 + \mathcal{P}(H_1)\mathcal{P}_d hP_1\right\} \\
&= \iint\limits_{\frac{h}{g}\leq\frac{\gamma_0}{\sigma^2}} \mathcal{P}(H_1)(1-\mathcal{P}_d)\alpha\frac{h}{g}f_h(h)f_g(g)dhdg \\
&\quad + \iint\limits_{\frac{h}{g}\leq\frac{\gamma_1}{\sigma^2}} \mathcal{P}(H_1)\mathcal{P}_d\alpha\frac{h}{g}f_h(h)f_g(g)dhdg \\
&= \int_0^{\frac{\gamma_0}{\sigma^2}} \mathcal{P}(H_1)(1-\mathcal{P}_d)\alpha\frac{u}{(u+1)^2}du \\
&\quad + \int_0^{\frac{\gamma_1}{\sigma^2}} \mathcal{P}(H_1)\mathcal{P}_d\alpha\frac{u}{(u+1)^2}du \\
&= \mathcal{P}(H_1)\alpha\left\{(1-\mathcal{P}_d)\left[\log\left(1+\frac{\gamma_0}{\sigma^2}\right) - \frac{\gamma_0}{\gamma_0+\sigma^2}\right]\right. \\
&\qquad\left. + \mathcal{P}_d\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1+\sigma^2}\right]\right\}.
\end{aligned}$$

2) Average Transmit Power: The average transmit power in (17) can be written as follows:

$$\begin{aligned}
&\mathbb{E}_{g,h}\{K_0P_0 + K_1P_1\} \\
&= \iint\limits_{\frac{h}{g}\leq\frac{\gamma_0}{\sigma^2}} \frac{K_0\alpha}{g}f_h(h)f_g(g)dhdg \\
&\quad + \iint\limits_{\frac{h}{g}\leq\frac{\gamma_1}{\sigma^2}} \frac{K_1\alpha}{g}f_h(h)f_g(g)dhdg \\
&= \int_0^{+\infty}\int_0^{\frac{\gamma_0 g}{\sigma^2}} \frac{K_0\alpha}{g}f_h(h)f_g(g)dhdg \\
&\quad + \int_0^{+\infty}\int_0^{\frac{\gamma_1 g}{\sigma^2}} \frac{K_1\alpha}{g}f_h(h)f_g(g)dhdg \\
&= K_0\alpha\log\left(1+\frac{\gamma_0}{\sigma^2}\right) + K_1\alpha\log\left(1+\frac{\gamma_1}{\sigma^2}\right).
\end{aligned}$$

3) Outage Probability: The outage probability for the cases of Sections IV-A and B is given by

$$\begin{aligned}
\mathcal{P}_{out} =& \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_0}{\sigma^2}\middle| H_0\right)\mathcal{P}(H_0)(1-\mathcal{P}_{fa}) \\
&+ \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_1}{\sigma^2}\middle| H_1\right)\mathcal{P}(H_1)\mathcal{P}_d \\
&+ \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_1}{\sigma^2}\middle| H_0\right)\mathcal{P}(H_0)\mathcal{P}_{fa} \\
&+ \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_0}{\sigma^2}\middle| H_1\right)\mathcal{P}(H_1)(1-\mathcal{P}_d) \\
=& \int_{\frac{\gamma_0}{\sigma^2}}^{+\infty} \frac{K_0}{(1+u)^2}du + \int_{\frac{\gamma_1}{\sigma^2}}^{+\infty} \frac{K_1}{(1+u)^2}du \\
=& \frac{K_0\sigma^2}{\gamma_0+\sigma^2} + \frac{K_1\sigma^2}{\gamma_1+\sigma^2}
\end{aligned}$$

where K_0 and K_1 are given by (22) and (23), respectively, and u denotes the random variable defined in Appendix B1.

4) Average Transmit Power Under High Target Detection Probability: The average transmit power in (36) can be written as

$$\begin{aligned}
&\mathbb{E}_{g,h}\{\bar{K}_0P_0 + \bar{K}_1P_1\} \\
&= \int_{\frac{\gamma_0}{\sigma^2}}^{+\infty} \bar{K}_0\frac{\alpha}{g}f_g(g)dg + \iint\limits_{\frac{h}{g}\leq\frac{\gamma_1}{\sigma^2}} \bar{K}_1\frac{\alpha}{g}f_h(h)f_g(g)dhdg \\
&= \alpha\left[\bar{K}_0\mathrm{E}_1\left(\frac{\gamma_0}{\sigma^2}\right) + \bar{K}_1\log\left(1+\frac{\gamma_1}{\sigma^2}\right)\right]
\end{aligned}$$

where $E_1(z) = \int_1^{+\infty} e^{-zt}t^{-1}dt,\ \mathrm{Re}\{z\} > 0$ denotes the exponential integral of order 1 [24].

5) Average Interference Power Under High Target Detection Probability: The average interference power in (37) can be written as follows:

$$\begin{aligned}
&\mathbb{E}_{g,h}\left\{\mathcal{P}(H_1)\bar{\mathcal{P}}_d hP_1\right\} \\
&= \iint\limits_{\frac{h}{g}\leq\frac{\gamma_1}{\sigma^2}} \mathcal{P}(H_1)\bar{\mathcal{P}}_d\alpha\frac{h}{g}f_h(h)f_g(g)dhdg \\
&= \int_0^{\frac{\gamma_1}{\sigma^2}} \mathcal{P}(H_1)\bar{\mathcal{P}}_d\alpha\frac{u}{(u+1)^2}du \\
&= \mathcal{P}(H_1)\bar{\mathcal{P}}_d\alpha\left[\log\left(1+\frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1+\sigma^2}\right]
\end{aligned}$$

where u denotes the random variable defined in Appendix B1.

6) Outage Probability Under High Target Detection Probability: The outage probability for the cases of Sections IV-C and D is given by

$$\begin{aligned}
\mathcal{P}_{out} =& \mathcal{P}\left(g < \frac{\gamma_0}{\sigma^2}\middle| H_0\right)\mathcal{P}(H_0)(1-\mathcal{P}_{fa}) \\
&+ \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_1}{\sigma^2}\middle| H_1\right)\mathcal{P}(H_1)\bar{\mathcal{P}}_d \\
&+ \mathcal{P}\left(\frac{h}{g} > \frac{\gamma_1}{\sigma^2}\middle| H_0\right)\mathcal{P}(H_0)\mathcal{P}_{fa} \\
&+ \mathcal{P}\left(g < \frac{\gamma_0}{\sigma^2}\middle| H_1\right)\mathcal{P}(H_1)(1-\bar{\mathcal{P}}_d) \\
=& \int_0^{\frac{\gamma_0}{\sigma^2}} \bar{K}_0 e^{-g}dg + \int_{\frac{\gamma_1}{\sigma^2}}^{+\infty} \frac{\bar{K}_1}{(1+u)^2}du \\
=& \bar{K}_0 - \bar{K}_0\exp\left(-\frac{\gamma_0}{\sigma^2}\right) + \frac{\bar{K}_1\sigma^2}{\gamma_1+\sigma^2}
\end{aligned}$$

where $\bar{K}_0$ and $\bar{K}_1$ are given by (22) and (23) for $\mathcal{P}_d = \bar{\mathcal{P}}_d$, and u denotes the random variable defined in Appendix B1.

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