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Throughput maximization of spectrum sharing cognitive radio networks

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ABSTRACT

Cognitive Radio technology helps in designing wireless system for efficient deployment of radio spectrum with its sensing technique,self adaptation and spectrum sharing. Spectrum sharing is an effective method of alleviating the scarcity of radio spectrum problem by allowing unlicensed users (secondary users) to coexist with licensed users (primary users) under the condition of protecting the later from harmful interference. This dissertation work emphasizes on the throughput maximization of spectrum sharing cognitive radio networks. It proposes an innovative spectrum sharing technique that will significantly improve achievable throughput of the network. This work introduces novel receiver and a frame structure for spectrum sharing. The problem of optimal power allocation that maximizes the ergodic capacity of the system under average transmits and interference power constraints are also studied.

Keywords: Cognitive radio, Ergodic capacity, Optimal power allocation, Spectrum sensing, Spectrum sharing, Throughput maximization.

INTRODUCTION

According to recent measurements by the federal communications commission (FCC), the current fixed spectrum allocation policy have resulted in several bands being severely underutilized both in temporal and spatial manner [4]. Hence the need for more available spectrum to develop better wireless services becomes increasingly pressing. Cognitive radio [7] 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 users to access licensed frequency bands, under the condition of protection the quality of service (QOS) of the licensed networks. This realization by the FCC of the inefficient use of the spectrum under the current fixed spectrum allocation policy led to the decision to allow access of unlicensed users to the broadcast television spectrum at locations where that spectrum is not being used by licensed services.

A. *Background*

Two main approaches have been developed for cognitive radio so far, regarding the way of secondary user accesses the licensed spectrum:

i. Through opportunistic spectrum access (OSA), also known as interweave scheme, according to which when frequency band is detected not being used by the primary users than it is accessed by a secondary user [9], and

ii. Through spectrum sharing (SS), also known as underlay scheme, according to which under the condition of protecting primary users from harmful interference secondary users coexist with them [1],[12]. Recently, in order to increase the throughput of the two afore mentioned schemes, a third hybrid approach was proposed, in which the secondary users sense for the status (active/idle) initially, 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) [11]. The frame structure of thus approach is same as in OSA and consists of a sensing slot and a data transmission slot.

A secondary user that employs this frame structure ceases data transmission at the beginning of each frame, perform spectrum sensing forτ units of time, in order to determine the status (active/idle) of the frequency band, and uses the remaining frame duration T-τ for data transmission. Therefore, an inherent tradeoff exists in this hybrid approach between the duration of spectrum sensing and data transmission. This tradeoff is studied in [11] and [8] for the ergodic throughput of cognitive radio networks and is similar to the one seen in OSA cognitive radio networks [10].

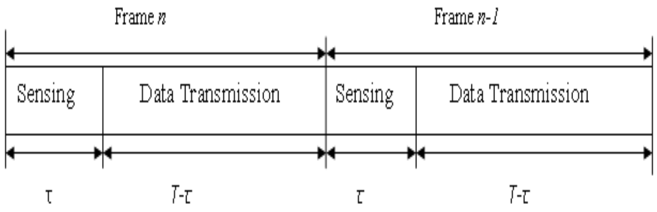

Figure 1: Frame structure of conventional sensing-based spectrum sharing

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.

B. *Methodology*

This dissertation work focusses on hybrid approach and considers it as amethod for improving the achievable throughput and proposes 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. In addition, the problem of maximizing the ergodic throughput of the proposed cognitive system under average transmit and interference power constraints that acquires the optimal power allocation strategy that maximizes the system's ergodic throughput.

I. Proposed Spectrum Sensing Scheme

A. *System Overview*

The proposed cognitive radio system operates as in Fig 2. 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 user communicate using higher transmit power i.e. P0 if the primary users are detected to be idle and lower power i.e. P1 otherwise.

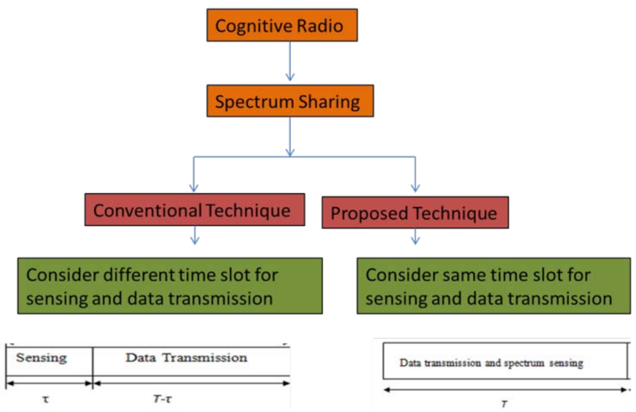

Figure 2: Proposed flow graph

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

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

where θdenotes the actual status of the frequency band (θ=1 if the frequency band is active, where asθ=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.

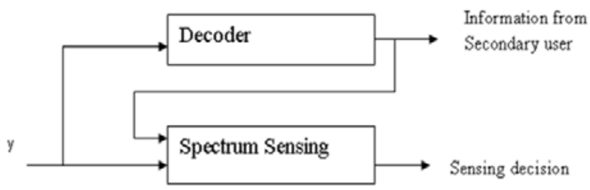

Figure 3: Receiver structure of the proposed cognitive radio system

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

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

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. 2), almost the whole duration of the frame T can be used for spectrum sensing under the proposed cognitive radio system. 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.

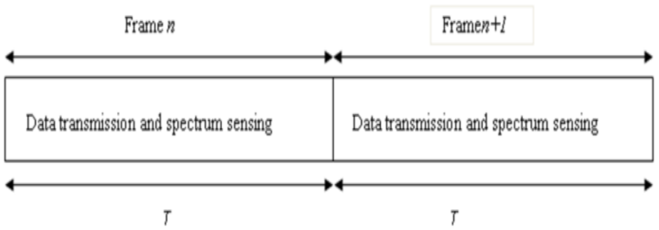

Figure 4: Frame structure of the proposed cognitive radio system

The significance of this result is twofold. First, under perfect cancellation, the increased sensing time:

- Enables the detection of very weak signals from the primary users, the detection of which under the frame structure of Fig. 4 would significantly reduce the data transmission time, hence the throughput of the cognitive radio system.
- Leads to an improved detection probability, thus better protection of 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 user from accessing an idle frequency band using higher transmit power, and therefore limits their achievable throughput.
- Facilitates the use of more complex spectrum sensing techniques that exhibit increased spectrum sensing capabilities, but requires higher sensing time (such as Cyclostationary detection, Generalised Likelihood Ratio Test (GLRT)- based or covariance-based spectrum sensing techniques), which prohibits their application for quick periodical spectrum sensing under the frame structure of Fig. 4.
- The calculation of the optimal sensing time is no longer an issue and does not require to be adapted or transmitted back to the secondary users;
- 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. 4 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 the data transmission on the other.

II. Network Model

In the cognitive radio system presented in Fig. 5 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) and the primary receiver (PU-Rx), respectively. The channel g and h are assumed to be ergodic, stationary and known at the secondary users with probability density function (pdf) $f_g(g)$ and $f_h(h)$, respectively, whereas the noise is assumed to be circularly symmetric complex guassian (CSCG) with mean zero and variance σ_n^2 namely $CN(0,\sigma_n^2)$ that in practice, it might be difficult to obtain perfect information of the channel h for fast fading channels. In the following, it is described how the proposed spectrum sharing scheme operates and present the receiver and frame structure employed in this cognitive radio system. 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.

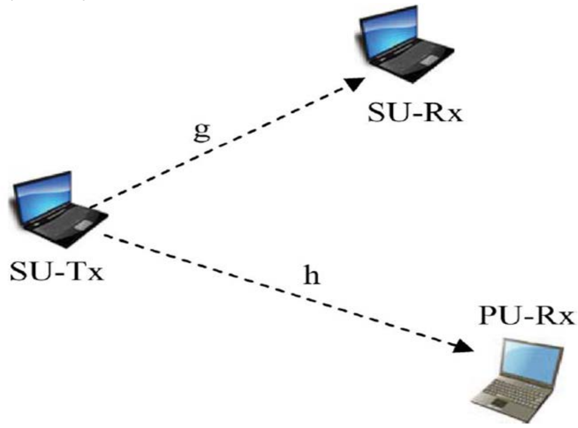

Figure 5: Proposed network model

III. Analytical Description Of Ergodic Capacity

In this section, the problem of deriving the optimal power allocation strategy that maximizes the ergodic capacity of the cognitive radio network that operates under the proposed spectrum sharing scheme is discussed. 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 [1], [2], [13], the instantaneous transmission rates when the frequency band is idle (H_0) and active (H_1) are given by

$$r_0 = \log_2\left(1+\frac{gp_0}{\sigma_n^2}\right),$$

$$r_1 = \log_2\left(1+\frac{gp_1}{\sigma_n^2+\sigma_p^2}\right) \qquad (3)$$

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, the perfect spectrum sensing may not be achievable in practice, where the actual status of the primary users might be falsely detected. Therefore, the 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 users present/absent) as follows:

$$r_{00} = \log_2\left(1 + \frac{g p_0}{\sigma_n^2}\right)$$

$$r_{01} = \log_2\left(1 + \frac{g p_1}{\sigma_n^2}\right)$$

$$r_{10} = \log_2\left(1 + \frac{g p_0}{\sigma_n^2 + \sigma_p^2}\right)$$

$$r_{11} = \log_2\left(1 + \frac{g p_1}{\sigma_n^2 + \sigma_p^2}\right)$$

Here, the first index number of the instantaneous transmission rates indicates the actual status of the primary users

("0" for 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, consider an average (over all fading states) transmit and interference power constraint that can be formulated as follows :

$$E_{g,h}\{P(H_0)(1-P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1-P_d)P_0 + P(H_1)P_dP_1\} \le P_{av} \quad (4)$$

$$E_{g,h}\{P(H_1)(1-P_d)hP_0 + P(H_1)P_d hP_1\} \le \Gamma \quad (5)$$

Where $P(H_0)$ and $P(H_1)$ denote the probability that the frequency band is idle and active, respectively, P_d and 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 primary users. The reason for choosing an average interference power constraint is based on the results in [14] and [11], which indicate that an average interference power constraints 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:

$$C = E_{g,h}\{P(H_1)P_d r_{11} + P(H_0)P_{fa} r_{01} + P(H_1)(1-P_d)r_{10} + P(H_0)(1-P_{fa})r_{00}\} \quad (6)$$

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

$$L(P_0, p_1, \lambda, \mu) = E_{g,h}\{P(H_1)P_d r_{11} + P(H_0)P_{fa} r_{01} + P(H_1)(1-P_d)r_{10} + P(H_0)(1-P_{fa})r_{00}\}$$
$$-\lambda E_{g,h}\{P(H_0)(1-P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1-P_d)P_0 + P(H_1)P_dP_1\} + \lambda P_{av} - \mu_{g,h} E_{g,h}\{P(H_1)(1-P_d)hP_0 + P(H_1)P_d hP_1\} + \mu\Gamma \quad (7)$$

Whereas the dual function can be obtained by

$$d(\lambda, \mu) = \sup L(P_0, P_1, \lambda, \mu) \quad (8)$$

In order to calculate the dual function $d(\lambda,\mu)$, the supremum of the langrangian with respect to the transmit powers P_0 and P_1 needs to be obtained. We therefore apply the primal-dual decomposition method [5], 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: maximize $\{P_0 \ge 0\}$

$$f_1(P_0) = E_{g,h}\left\{P(H_0)(1-P_{fa})\log_2\left(1+\frac{g p_0}{\sigma_n^2}\right) + P(H_1)(1-P_d)\log_2\left(1+\frac{g p_0}{\sigma_n^2+\sigma_p^2}\right)\right\}$$
$$- \Lambda E_{g,h}\{P(H_0)(1-P_{fa})P_0 + P(H_1)(1-P_d)P_0\} - \mu E_{g,h}\{P(H_1)(1-P_d)hP_0\} \quad (9)$$

Subproblem 2: maximize $\{P_1 \ge 0\}$

$$f_2(P_1) = E_{g,h}\left\{P(H_0)P_{fa}\log_2\left(1+\frac{g p_1}{\sigma_n^2}\right) + P(H_1)P_d\log_2\left(1+\frac{g p_1}{\sigma_n^2+\sigma_p^2}\right)\right\} - \lambda E_{g,h}\{P(H_0)P_{fa}P_1 + P(H_1)P_dP_1\} - \mu E_{g,h}\{P(H_1)P_d hP_1\} \quad (10)$$

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)

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

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

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

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

And the parameters in above equations are given by

$$\alpha_0 = P(H_0)(1-P_{fa})$$
$$\beta_0 = P(H_1)(1-P_d)$$
$$\alpha_1 = P(H_0)P_{fa}$$
$$\beta_1 = P(H_1)P_d$$

IV. Conclusion

This dissertation work is proposed to maximize the throughput in cognitive radio network. It proposes an innovative spectrum sharing technique that will significantly improve achievable throughput of the network. This work introduces novel receiver and a frame structure for spectrum sharing in which spectrum sensing and data transmission is done simultaneously. The problem of optimal power allocation that maximizes the ergodic capacity of the system under average transmits and interference power constraints are also studied.

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