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Improved Cognitive Radio Receivers Using Timing Mismatch of Primary and Secondary Users

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***Abstract*—We consider an asynchronous cognitive radio framework, where the primary user (spectrum license holder) and the secondary user are, naturally, not aligned in their timing. We show that applying our optimal receiver design results in improving the performance compared to the case of synchronous cognitive radio. We optimize the rates subject to the constraint to keep interference imposed on the primary user below a certain level. We also derive the constraint for the receiver of the secondary user to perform interference cancellation. Simulation results show that our proposed oversampling secondary user receiver boosts the received signal. As a result, the secondary user's transmission power can be decreased without negatively affecting the quality of the received signal. Not only does our method reduce the interference to the primary user, but also it saves power at the secondary user.**

I. Introduction

In overlay selfless cognitive radio networks (CRNs), the primary user (PU) and the secondary user (SU) use the same band simultaneously conditioned that the SU allocates a percentage (α) of its power to relay the PU's message [1]. In an example overlay CRN scenario, the SU acts as a relay to forward the PU's message in order to undo the effects of interference to the PU. In particular, overlay cognitive radio is useful when the link between the PU transmitter and the PU receiver is weak, whereas the quality of the channel between the SU transmitter and the PU receiver is better. In this case, the PU and SU use overlay CRN framework, i.e., the PU allows the SU to use the band for SU message transmission using $1-\alpha$ percent of SU's power, while the SU helps the PU by relaying the PU's message using α percent of its power. In [2], power consumption of CRNs is considered while satisfying the PU and SU's signal-to-interference-plus-noise ratio (SINR) constraints. Practically speaking, the signals of PU and SU are not synchronized since they are two different users. This motivates us to show that the performance of CRNs can be improved by natural time-asynchrony as the result of designing optimal cognitive radio receivers. No prior work has paid attention to the benefits of using oversampling at the SU receiver subject to constraints for the protection of PU priority and SU interference cancellation in asynchronous CRNs. Accordingly, a direct result of our method is that there is no need for extra circuits to synchronize [3], [4] the PU and SU. To this end, we use oversampling at the SU's receiver to take advantage of the asynchrony of PU and SU toward enhancing the SU's received signal. To do so, the SU transmitter must allocate a smaller percentage $(1-\alpha)$ of its power to communicate with the SU receiver. Therefore, SU's power is conserved in addition to reducing interference on the PU receiver.

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The *main contributions* of this paper are formulating the optimization problems aiming at maximizing the rates, while enabling the SU to perform interference cancellation, and constraining the interference on the PU by an SU receiver design that exploits timing mismatch of PU and SU signals.

A. Review of Relevant Work

Han *et al.* [5] consider cooperative spectrum sharing between a PU and SUs based on relaying. First, one relay is selected to help with the transmission of the PU message by providing a target rate. After this phase, another SU can use the band simultaneously since the relay makes the PU more robust against interference. Another study of cooperative spectrum sharing [6] considers an overlay CRN in which the SU forwards the PU's message to the PU receiver by allocating α percent of its power. This investigates the effects of α on the PU's outage compared to a case where the SU is not sharing the spectrum with the PU. In a cooperative CRN, the SU may know the PU's modulation scheme [7]. The SU uses this knowledge to superimpose its own modulated signal on the PU's signal. This spectrum sharing scheme does not degrade the PU's performance while enhancing the probability of error for the SU. Shao *et al.* [8] intentionally apply delay offsets to a Vertical-Bell Labs layered space-time (V-BLAST) system. They use zero forcing detection to increase diversity thereby asynchronously improving the bit error rate performance compared to synchronous V-BLAST systems. Avendi *et al.* [9] consider non-synchronized distributed relays in differential space-time coding. In this regard, they present differential encoding and decoding schemes for distributed differential space-time coding systems [10] with multiple asynchronous relays. They show that their asynchronous method is more robust than a synchronous system in terms of sensitivity to synchronization errors. In addition, the authors of [11] design differential detection schemes for asynchronous multi-user MIMO systems based on orthogonal space-time block codes [12]. They show that the proposed asynchronous schemes outperform their synchronous counterparts.

As discussed in the above-mentioned works, asynchronous communication systems yield improved performance over synchronous systems. Nevertheless, rather less attention is being paid to asynchronous cognitive radio networks. In [13], we introduced the usage of symbol asynchrony in CRNs toward improving the performance of spectrum sharing systems. Contrary to [13], in this paper we focus on the SU receiver design and present the pertinent oversampling equations. In addition, we optimize the CRN data rates subject to constraints aiming at allowing the SU to perform interference cancellation at its receiver and to keep its interference to the PU below a permissible threshold.

The rest of the paper is organized as follows. Section II presents the design of an asynchronous CRN. Section III includes the numerical results supporting the effectiveness of the proposed solutions. Finally, Section IV concludes the paper.

II. Optimum Asynchronous CRNs with Limited Interference on the PU

We consider a cognitive selfless overlay relay network as in Fig. 1.

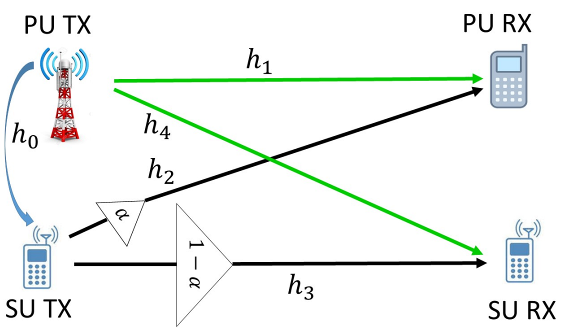

Fig. 1. A selfless overlay cognitive radio with channel coefficients h_0, h_1, h_2, h_3, and h_4.

The SU dedicates a fraction (α) of its power to relay the PU's message x_1 and the remaining $(1-\alpha)$ percent of its power to transmit the SU's own message x_3. In [13], we show that making the realistic assumption of asynchronous signal reception at PU and SU receivers leads to having larger values of SINR. In selfless overlay CRNs and when the PU's message relayed by the SU's[1] transmitter is completely synchronized with the PU's direct message, the received signal at the PU's receiver is given by

$$y_p(t) = \underbrace{h_1 \sqrt{P_1} x_1(t)}_{\text{PU message}} + \underbrace{h_2 \sqrt{\alpha P_2} x_2(t)}_{\text{relayed message}} + \underbrace{h_2 \sqrt{(1-\alpha) P_2} x_3(t)}_{\text{CR interference}} + n_P(t). \tag{1}$$

In Eq. (1), the transmission powers of PU and SU are denoted by P_1 and P_2, respectively. Further, $x_2(t)$ and $n_P(t)$ are the relayed PU's message by the SU and noise at the PU's receiver, respectively. Channel coefficients h_1 and h_2 are shown in Fig. 1. We deploy an oversampling scheme at the SU receiver as in Fig. 2 of [13] to capture the timing mismatch τ between the PU and SU. The timing mismatch is a fraction of the symbol time T_s.

[1]We use the terms SU and CR interchangeably.

Contrary to [13] in which we designed an optimal receiver for the PU, here we design an optimal receiver for the SU aiming at taking advantage of asynchrony between PU and SU. In addition, we present optimization objectives and constraints related to data rates (or SINRs). We further show that by oversampling at the SU receiver, asynchronous CRNs consume less power compared to synchronous CRNs thereby satisfying PU and SU requirements.

Here, the SU (i.e., CR) is using superposition coding [14]. Since PU and CR are not synchronous, we can take two samples per symbol at the CR's receiver, as shown in Fig. 2. For

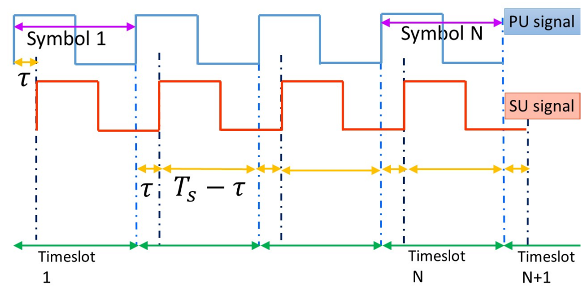

Fig. 2. Our scheme for double sampling per symbol at the SU receiver.

example and for the n-th transmitted symbol, the oversampling CR receiver obtains $y_C^{n,1}$ and $y_C^{n,2}$ as in Eq. (2) on Page 3. In Eq. (2), $p(\tau)$ is the sampled signal after pulse shaping and matched filtering with the raised cosine pulse. In addition and for $i \in \{1, 2\}$ at the n-th symbol time, $n_{SR}^{n,i}$ denotes the i-th sample of noise at the SU receiver and $n_{ST}^{n,i}$ represents the i-th noise sample at the receiving module of the SU transmitter. Since the PU interference and the desired SU signals arrive with delay at the SU receiver, the SU receiver captures the peak of one of the signals along with the tail of another signal if it samples twice per time slot. On the contrary, the distinction between the two samples per symbol in Fig. 2 vanishes in the case of synchronous CRNs in which $\tau = 0$. The latter is the reason why asynchronous CRNs outperform their synchronous counterparts. In other words, gaining access to two distinct samples per symbol boosts the received signal compared to having only one sample per symbol. Unlike [13] where interference on PU was caused by the SU signal, the interference on the SU receiver is caused by two terms here, i.e., the PU's signal and the relayed PU's message by the SU transmitter.

To write Eq. (2) in matrix form for N transmitted symbols, denote the matrix of asynchronous received SU signals by $\mathbf{Y}_C^A = [y_C^{1,1}\ y_C^{1,2}\ \ldots\ y_C^{n,1}\ y_C^{n,2}\ \ldots\ y_C^{N,1}\ y_C^{N,2}\ y_C^{N+1,1}]$. Then, $\mathbf{Y}_C^A = \mathbf{G}_D^A \mathbf{X}_3 + \mathbf{G}_U^A \mathbf{X}_1 + \mathbf{N}_{SR}^A$, where the matrix $\mathbf{G}_D^A$ is the asynchronous overlay CRN channel from the SU transmitter to the SU receiver. In addition, $\mathbf{G}_U^A$ is the asynchronous overlay CRN interference channel between the PU transmitter and the SU receiver. The superscript A denotes asynchronous CRN, the subscript D denotes desired, and the subscript U denotes undesired. $\mathbf{N}_{SR}^A$ denotes the vector of sampled noise at the SU receiver in asynchronous CRN. Contrary to the PU receiver, the desired received signal for the SU receiver is $\mathbf{X}_3 = [x_3^1\ x_3^2\ \ldots\ x_3^n\ \ldots\ x_3^N]^T$ which is sent by the SU transmitter

$$y_C^{n,1} = h_3\sqrt{(1-\alpha)P_2}p(\tau)x_3^n + h_3\sqrt{(1-\alpha)P_2}(1-p(\tau))x_3^{n-1} + \underbrace{\left(h_4\sqrt{P_1}+h_3h_0\sqrt{\alpha P_2P_1}p(\tau)\right)x_1^n + h_3h_0\sqrt{\alpha P_2P_1}(1-p(\tau))x_1^{n-1}}_{\text{interference}} + n_{SR}^{n,1} + \sqrt{\alpha}n_{ST}^{n,1}h_3\sqrt{P_2}$$

$$y_C^{n,2} = h_3\sqrt{(1-\alpha)P_2}x_3^n + \underbrace{\left(h_4\sqrt{P_1}p(\tau)+h_3h_0\sqrt{\alpha P_2P_1}\right)x_1^n + h_4\sqrt{P_1}(1-p(\tau))x_1^{n+1}}_{\text{interference}} + n_{SR}^{n,2} + \sqrt{\alpha}n_{ST}^{n,2}h_3\sqrt{P_2}. \quad (2)$$

and is intended for the SU receiver. In addition, the undesired signal at the SU receiver is $\mathbf{X}_1 = [x_1^1\ x_1^2\ \ldots\ x_1^n\ \ldots\ x_1^N]^T$ which is intended for the PU receiver.

Similarly, we can write the vector of received signals at the SU receiver in synchronous overlay CRN as $\mathbf{Y}_C^S = \mathbf{G}_D^S\mathbf{X}_3 + \mathbf{G}_U^S\mathbf{X}_1 + \mathbf{N}_{SR}^S$, where the synchronous notation is defined by replacing A with S in the asynchronous notation.

To write the SINR at the SU receiver, we calculate the matrix norms as in Eq. (3) on Page 4. In Eq. (3), σ_{sr}^2 is the noise power at the SU receiver and σ_{st}^2 is the noise power at the receiving module of the SU transmitter.

The following constraint then protects the PU from interference in asynchronous CRNs.

$$\|\mathbf{H}_D^A\|_F^2 > \|\mathbf{H}_U^A\|_F^2, \quad (4)$$

where $\|.\|_F$ denotes the Frobenius norm. As defined in [13], $\mathbf{H}_D^A$ is the matrix of the asynchronous overlay CRN channel from the PU and SU transmitters to the PU receiver. Furthermore, $\mathbf{H}_U^A$ is the matrix of the asynchronous overlay CRN interference channel between the SU transmitter and the PU receiver. To obtain the constraint in synchronous CRNs protecting the PU from interference, we replace the superscript A with S in Eq. (4). We derive the norms of $\mathbf{H}_D^A$, $\mathbf{H}_U^A$, $\mathbf{H}_D^S$, and $\mathbf{H}_U^S$ in [13]. Besides, considering that the SU receiver performs interference cancellation to remove the undesired PU's signal, the SU rate with timing mismatch is $R_c^A = \log_2\left(1+\frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right)$. Similarly, we obtain the SU rate without timing mismatch, i.e., R_c^S by replacing superscript A with S. The condition for the SU receiver to be able to perform interference cancellation in the asynchronous CRNs is

$$\frac{\|\mathbf{G}_U^A\mathbf{X}_1\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2} > \frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}. \quad (5)$$

A similar expression can be derived for synchronous CRNs by replacing the superscript A with S in Eq. (5).

A. Optimization Formulations

We are now ready to formalize and compare the optimization problems for the asynchronous and synchronous PU and SU in overlay CRNs. The objective is to maximize R_c^A and R_c^S, i.e., the rate of SU, subject to the above-mentioned constraints, i.e., protection of PU from interference and interference cancellation at the SU. Therefore, the optimization problem is formulated as

$$\begin{aligned} \max_{\alpha,\tau}\ & R_c^A = \log_2\left(1+\frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right) \\ \text{s.t.}\ & \|\mathbf{H}_D^A\|_F^2 > \|\mathbf{H}_U^A\|_F^2 \\ & \log_2\left(1+\frac{\|\mathbf{G}_U^A\mathbf{X}_1\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right) > \log_2\left(1+\frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right) \\ & 0 \le \alpha \le 1 \\ & 0 \le \tau \le T_s \end{aligned} \quad (6)$$

With synchrony, the optimization problem is

$$\begin{aligned} \max_{\alpha}\ & R_c^S = \log_2\left(1+\frac{\|\mathbf{G}_D^S\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right) \\ \text{s.t.}\ & \|\mathbf{H}_D^S\|_F^2 > \|\mathbf{H}_U^S\|_F^2 \\ & \log_2\left(1+\frac{\|\mathbf{G}_U^S\mathbf{X}_1\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right) > \log_2\left(1+\frac{\|\mathbf{G}_D^S\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right) \\ & 0 \le \alpha \le 1 \end{aligned} \quad (7)$$

We solve the optimization problem (6), to jointly find the optimal values of delay τ and α. To show the benefits of asynchrony for CRNs, we also solve the optimization problem (7), which solely depends on α and demonstrate that α in the former problem has a lower value due to the delay parameter τ. This results in saving the SU's power without degrading the PU's and SU's received signals.

B. Optimization Solution

In this subsection, we provide our approach to solving the optimization problems of the previous subsection. Relying on the Lagrangian theory, we convert the problems of interest to optimization problems without constraints. We define the Lagrangian function associated with Problem (6) as

$$\begin{aligned} LG_A =\ & \log_2\left(1+\frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right) + \mu_1\left(\|\mathbf{H}_D^A\|_F^2 - \|\mathbf{H}_U^A\|_F^2\right) \\ & + \mu_2\left[\log_2\left(1+\frac{\|\mathbf{G}_U^A\mathbf{X}_1\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right) - \log_2\left(1+\frac{\|\mathbf{G}_D^A\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^A\|_F^2}\right)\right] \\ & + \mu_3\left(1-\alpha\right) + \mu_4\left(T_s-\tau\right) \end{aligned} \quad (8)$$

where the parameters μ_k with $k = 1,2,3,4$ are the Lagrange multipliers in the Lagrangian Eq. (8). Similarly, the Lagrangian function associated with Problem (7) is defined as

$$\begin{aligned} LG_S =\ & \log_2\left(1+\frac{\|\mathbf{G}_D^S\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right) + \mu_1\left(\|\mathbf{H}_D^S\|_F^2 - \|\mathbf{H}_U^S\|_F^2\right) \\ & + \mu_2\left[\log_2\left(1+\frac{\|\mathbf{G}_U^S\mathbf{X}_1\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right) - \log_2\left(1+\frac{\|\mathbf{G}_D^S\mathbf{X}_3\|_F^2}{\|\mathbf{N}_{SR}^S\|_F^2}\right)\right] \\ & + \mu_3\left(1-\alpha\right) \end{aligned} \quad (9)$$

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$$
\begin{aligned}
&||\mathbf{N}_{SR}^{A}||_F^2 = (2N+1)\left(\sigma_{sr}^2 + \alpha\sigma_{st}^2|h_3|^2P_2\right) \\
&||\mathbf{N}_{SR}^{S}||_F^2 = N\left(\sigma_{sr}^2 + \alpha\sigma_{st}^2|h_3|^2P_2\right) \\
&||\mathbf{G}_{D}^{A}||_F^2 = ||h_3(1-\alpha)\sqrt{P_2}p(\tau)||^2 + N||h_3\sqrt{(1-\alpha)P_2}||^2 + (N-1)||h_3\sqrt{(1-\alpha)P_2}p(\tau) + h_3\sqrt{(1-\alpha)P_2}(1-p(\tau))||^2 + ||h_3\sqrt{(1-\alpha)P_2}(1-p(\tau))||^2 \\
&||\mathbf{G}_{D}^{S}||_F^2 = N\left(|h_3|^2(1-\alpha)P_2\right) \\
&||\mathbf{G}_{U}^{A}||_F^2 = N||h_4\sqrt{P_1} + h_3h_0\sqrt{\alpha P_1P_2}p(\tau)||^2 + N||h_4\sqrt{P_1}p(\tau) + h_0h_3\sqrt{\alpha P_1P_2}||^2 + ||h_3h_0\sqrt{\alpha P_1P_2}p(\tau)||^2 + (N-1)||h_3h_0\sqrt{\alpha P_1P_2}(1-p(\tau))||^2 + (N-1)||h_4\sqrt{P_1}(1-p(\tau))||^2 \\
&||\mathbf{G}_{U}^{S}||_F^2 = N||h_4\sqrt{P_1} + h_0h_3\sqrt{\alpha P_1P_2}||^2
\end{aligned}
\tag{3}
$$

The unconstrained optimization problems associated with the two problems above are then defined, respectively, as

$$\max_{\alpha,\tau} LG_A \tag{10}$$

and

$$\max_{\alpha} LG_S \tag{11}$$

Conditions of Optimality: Constraint Qualifications

We now investigate the existence of necessary and sufficient optimality conditions also known as constraint qualifications for Problem (6). Similar conditions exist for Problem (7) but are omitted here for brevity. For the unconstrained minimization problem (10), constraint qualifications are expressed in terms of Lagrange multiplier theory [15]. They revolve around conditions under which Lagrange multiplier vectors satisfying the following conditions are guaranteed to exist for a local optimum $\{\alpha^*, \tau^*\}$. The local optimum satisfies

$$\nabla LG_A(\alpha^*, \tau^*) = 0, \tag{12}$$

where $\nabla LG_A = [\frac{\partial LG_A}{\partial \alpha}, \frac{\partial LG_A}{\partial \tau}]$. Further, $\mu_k^* \geq 0$ for $k = 1,2,3,4$ if associated with an active inequality at (α^*, τ^*), i.e.,

$$\begin{cases} \mu_1^* \geq 0 & : \ \text{if } (||\mathbf{H}_D^A||_F^2 = ||\mathbf{H}_U^A||_F^2) \\ \mu_1^* = 0 & : \ \text{otherwise} \end{cases} \tag{13}$$

$$\begin{cases} \mu_2^* \geq 0 & : \ \text{if } \left(\log_2\left(1 + \frac{||\mathbf{G}_U^A\mathbf{X}_1||_F^2}{||\mathbf{N}_{SR}^A||_F^2}\right) = \log_2\left(1 + \frac{||\mathbf{G}_D^A\mathbf{X}_3||_F^2}{||\mathbf{N}_{SR}^A||_F^2}\right)\right) \\ \mu_2^* = 0 & : \ \text{otherwise} \end{cases} \tag{14}$$

$$\begin{cases} \mu_3^* \geq 0 & : \ \text{if } (\alpha = 1) \\ \mu_3^* = 0 & : \ \text{otherwise} \end{cases} \tag{15}$$

and

$$\begin{cases} \mu_4^* \geq 0 & : \ \text{if } (\tau = T_s) \\ \mu_4^* = 0 & : \ \text{otherwise} \end{cases} \tag{16}$$

Constraint qualifications guarantee the existence of unique Lagrange multipliers for a given local minimum (α^*, τ^*) if the active inequality constraint gradients of Problem (6) are linearly independent.

We note that the objective function of Problem (6) defined over a compact subset of $\mathcal{R}^2$ is continuously differentiable and the associated constraint gradients are linearly independent. Finding the solution to the optimization problem is, therefore, equivalent to finding the solution to unconstrained optimization problem (12) specifying decision variables (α^*, τ^*).

Considering the fact that the associated constraints are convex, we propose deploying the Sequential Quadratic Programming (SQP) technique. In SQP, the necessary conditions for optimality are represented by the Kuhn-Tucker (KT) equations described by Equation (12) and the conditions below.

$$
\begin{aligned}
&\mu_1^* \, (||\mathbf{H}_D^A||_F^2 * - ||\mathbf{H}_U^A||_F^2 *) = 0 \\
&\mu_2^* \left(\log_2\left(1 + \frac{||\mathbf{G}_U^A\mathbf{X}_1||_F^2 *}{||\mathbf{N}_{SR}^A||_F^2 *}\right) - \log_2\left(1 + \frac{||\mathbf{G}_D^A\mathbf{X}_3||_F^2 *}{||\mathbf{N}_{SR}^A||_F^2 *}\right)\right) = 0 \\
&\mu_3^* \, (1 - \alpha^*) = 0 \\
&\mu_4^* \, (T_s - \tau *) = 0 \\
&\mu_1^*, \mu_2^*, \mu_3^*, \mu_4^* \geq 0
\end{aligned}
\tag{17}
$$

A variant of the quasi-Newton method can then be used to iteratively find the solution to the optimization problem [16]. We note that utilizing a variant of the quasi-Newton method is equivalent to solving a quadratic estimation of the problem in every iteration.

We end this section by providing an analysis of complexity for solving the problem above. The time complexity of solving the problem of (12) is in the order of $O(Ik\log k)$ where I indicates the number of iterations and k indicates the degree of quadratic estimation.

III. Simulation Results

Fig. 3 compares the optimal values of power splitting ratio by solving optimization problems (6) and (7) for asynchronous and synchronous overlay CRNs, respectively. We randomly select the initial guess for the solution. In other works [11] $\tau = 0.5T_s$ was shown to be the optimal value. Therefore, our initial starting point for the optimization simulation is $\tau = 0.5T_s$. Note that in the synchronous CRN, $\tau = 0$. The value of raised cosine roll-off factor is $\beta = 0.9$ and the number of transmitted symbols is $N = 100$. The ratio of SU to PU power or $\frac{P_2}{P_1}$ varies. As Fig. 3 shows, the value of power consumption factor, i.e., α in the asynchronous CR scheme is less than its synchronous counterpart due to delay τ. For $P_2/P_1 = 2$, Fig. 3 shows almost 20% improvement in power. Fig. 4 compares the resulting α parameters versus the SU's power for two different ratios of PU to SU power, i.e., the cases of $P_2 = 0.5P_1$ and $P_2 = 2P_1$. In each case, the asynchronous scheme outperforms its

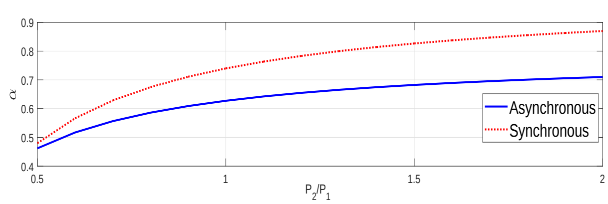

Fig. 3. A comparison of optimal power splitting parameter α for asynchronous and synchronous overlay CRNs.

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synchronous counterpart. The asynchronous CR yields a lower power consumption factor α compared to the synchronous CR, because of the delay variable τ. Fig. 5 shows the superior

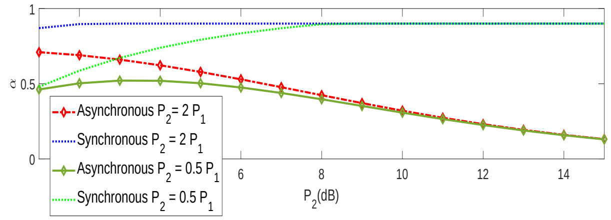

Fig. 4. A comparison of optimal power splitting parameters versus P_2, for different power ratios, for asynchronous and synchronous overlay CRNs.

data rate performance of asynchronous SU receiver compared with the synchronous SU receiver. Finally, Fig. 6 demonstrates

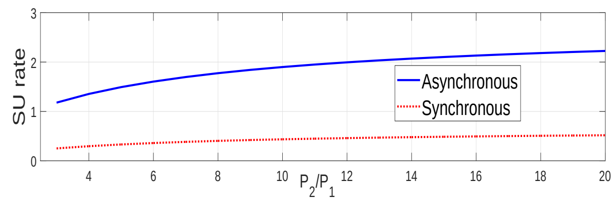

Fig. 5. A comparison of optimized SU data rates versus different power ratios, for asynchronous and synchronous overlay CRNs.

optimal values of α as functions of the ratio of PU to SU power, when the SU's power is fixed to three values of 0 dB, 6 dB, and 10 dB. Fig. 7 shows the interference suppression

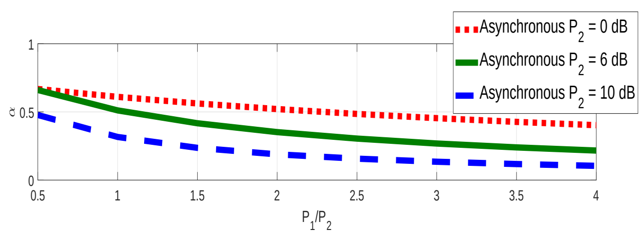

Fig. 6. A comparison of optimal power splitting parameter α versus PU to SU power ratio for asynchronous overlay CRN with $P_2 = 0$ dB, $P_2 = 6$ dB, and $P_2 = 10$ dB.

capability of asynchronous CRNs.

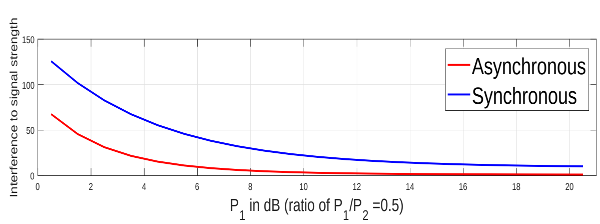

Fig. 7. Interference to desired signal strength in asynchronous and synchronous CRNs for $P_1/P_2 = 0.5$.

IV. Conclusion

We formulated optimization problems for asynchronous and synchronous cognitive radio schemes and showed that by proper design of cognitive radio receivers, we can harness the benefits arising from the natural timing mismatch between the primary and secondary users. In particular, we used oversampling at the SU receiver. Our optimization problems included maximum data rates and constraints aimed at protecting the spectrum license holder, i.e., the PU, from interference, while enabling the SU receiver to cancel interference. Our formulations demonstrated the superior performance of the asynchronous CRN over synchronous CRN. In other words, the asynchronous CRN achieves the same objective values with smaller power consumption compared to the synchronous CRN due to the delay parameter. Our deployed oversampling scheme at the cognitive radio receiver resulted in boosting the received signal and decreased the CRN power to protect the PU from interference. While the asynchronous system provides more power efficiency, higher data rates, and robustness against sensitivity to synchronization errors, compared to the synchronous system, its decoder is more complex.

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