A Novel Cognitive Modulation Method Considering the Performance of Primary User

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***Abstract*—This paper proposes a new modulation method for an uncoded cognitive transmission (secondary user transmission) in presence of a Primary User (PU) for the AWGN channel. Interference of the PU is assumed to be known at the transmitter of Cognitive User (CU) non-causally. Based on this knowledge, for the design of the modulator and demodulator of the CU, a symbol by symbol approach is studied which can fulfill the coexistence conditions of the CU and the PU of the band. In this scheme, the modulator and demodulator of CU are designed jointly by solving an optimization problem to mitigate the interference of the PU and minimize the symbol error probability (P_e) in CU's communication link without increasing the symbol error probability (P_e) of the PU. The proposed method is a modulation approach in a single (complex-valued) dimension rather than a high dimensional coding scheme. Although this one-dimensional method is not capacity achieving, we show it still has a remarkable performance with low amount of complexity. An implementation algorithm for our modulation method is also presented and the performance of this method is evaluated by experimental results.**

***Index Terms*—Cognitive Radio, Costa Precoding, Dirty Paper Coding, Relay, Interference Channel, Modulation, Uncoded Communication, Interference Avoidance.**

I. Introduction

According to recent studies of Federal Communication Commission (FCC), the licensed spectrum is severely underutilized [1]. Therefore, *Cognitive Radio* is recommended for dynamic and secondary spectrum licensing by FCC as an option to reduce the amount of unused spectrum [2]. The concept of cognitive radio–a wireless device that can sense and adapt to the spectrum–was first introduced by J. Mitola [3]. There have been several information-theoretical studies on achievable rates and modeling of cognitive radio networks during recent years (e.g., [4] and [5]). In [4], both links of Primary User (PU) and Cognitive User (CU) are error free with infinite length codewords. In addition, PU and CU cooperate and jointly design their encoder and decoder pairs. In reality, the problem is often different. The PUs are radio devices which have fixed and non-adaptive designs, and they cannot change their encoding and decoding procedure jointly with the CUs. A more realistic study of cognitive radio for the additive Gaussian case is done in [5], where the cognitive transmission is studied based on two coexistence conditions:

1) The PU is not aware of the presence of the CU. It has a fixed transmitter-receiver and is not capable of adapting to the CU's transmission.
2) The CU should not degrade performance of the PU's link by introducing the harmful interference.

The problem of cognitive transmission is an extension of designing the transmitter and the receiver for cancellation of the known interference at the transmitter. For this interference cancellation case, dirty paper coding (DPC) or Costa precoding has been suggested in [6]. The main difference of DPC compared to the cognitive scenario is that the effect of the interfered user (cognitive user) on the performance of the interferer's (non-cognitive user) link is neglected in DPC. This method is denoted as *selfish*, since the CU does not care about the non-cognitive user [7]. On the other hand, another case can be studied in which the CU can act as a relay based on the knowledge of the non-cognitive user's transmitted signals. In this case, the CU disregards performance of its own link and fully relays the non-cognitive user's messages; This method is called *selfless* [7].

In several previous studies on cognitive transmission (e.g., [5]) a proper combination of selfish and selfless scenarios (DPC and Relay) is suggested in order to fulfill the mentioned coexistence conditions. Although these information-theoretical schemes introduce acceptable achievable rates for coded cognitive radio channels, the infinite length of the codewords (infinite time intervals) and high dimensional coding make them complex for practical implementations.

To reduce the complexity, we propose a practical method for the cognitive transmission in one dimension (a complex-valued dimension). It means that, instead of using the whole sequence of the known PU codeword (PU interference), a single transmitted symbol of the PU in each channel use is exploited to produce the transmitted symbol of the CU. Although the performance of this method is wore than the case in which the whole sequence of interference is used, we will show this low complexity method still has a remarkable performance.

The design of the optimal modulator-demodulator pair for cancellation of known interference in one dimension based on a symbol by symbol method is recently studied in [8]. In [8], unlike our proposed method, the interferer is not necessarily a user and its performance is not analyzed in presence of the interfered user (cognitive user). Therefore, we first reintroduce the method of [8] but for the case in which the interferer is also a user. For convenience, the term *optimal cancellation* is used

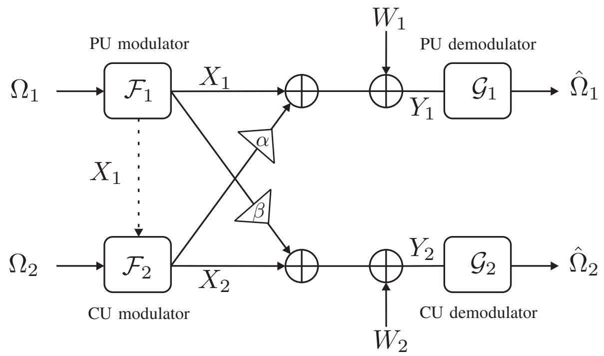

Fig. 1: System Model.

here to refer to this method. Then, a new scheme for designing the modulator and demodulator of the CU for an uncoded relay channel is presented. We use the term *full relay* for referring to this method. Finally, a practical combination of these two methods for designing the modulator and demodulator of the CU is presented, which can fulfill the coexistence conditions of our uncoded cognitive transmission.

Here, the primary and cognitive transmissions are considered erroneous in the same way as real communication links which is another difference of our case and the information-theoretical studies (e.g., [4] and [5]). As it is a one dimensional method, instead of using the information-theoretical rates, the performance of the primary and cognitive user's links for different scenarios are evaluated by calculation of the symbol error probability (P_e) of each link.

II. Mathematical Formulation of The Model

Information messages of the PU, Ω_1, is a discrete random variable uniformly distributed over the set $\{\omega_{1,1},\ldots,\omega_{1,M_1}\}$. During each channel use, one of the realizations of the Ω_1 is transmitted. This message is modulated by the modulator function $\mathcal{F}_1 : \{\omega_{1,1},\ldots,\omega_{1,M_1}\} \to X_1 \in \mathbb{C}$ of the PU. The output of $\mathcal{F}_1$ is the complex-valued transmitted signal of X_1. At the receiver, a complex Gaussian noise W_1, zero mean with variance equal to σ_1^2 is added to the X_1. The received signal $Y_1 = \mathcal{F}_1(\Omega_1) + W_1 = X_1 + W_1$ is demodulated by the demodulation function $\mathcal{G}_1 : Y_1 \in \mathbb{C} \to \{\omega_{1,1},\ldots,\omega_{1,M_1}\}$.

Due to our model, in which the PU has a fixed and non-adapting design, $\mathcal{F}_1$ and $\mathcal{G}_1$ are two fixed functions and cannot be adapted in presence of the CU. For the given demodulator of the PU, decision regions $\mathcal{B}_{\omega_{1,i}}$ are also fixed and can be defined as

$$\mathcal{B}_{\omega_{1,i}} = \{y_1 | \mathcal{G}_1(y_1) = \omega_{1,i}\}, \quad i = \{1,\ldots,M_1\} \tag{1}$$

which is the set of received signals y_1 that results in the output $\omega_{1,i}$ of the demodulator function.

Following [5], we assume the *Standard Form* for the cognitive radio channel, where the direct channel gain between the transmitter and receiver of the PU is equal to one. The gain of the cross talk channel (interference) between the transmitter of the CU and the receiver of the PU is equal to α. In this case the received signal of the PU is $Y_1 = \mathcal{F}_1(\Omega_1) + W_1 + \alpha X_2 = X_1 + W_1 + \alpha X_2$ where X_2 is the complex-valued transmitted signal of the CU that will be introduced in more detail later.

In the single PU case where the CU is not present (or $\alpha = 0$), the average symbol error probability of the PU using the demodulation function $\mathcal{G}_1(Y_1) = \hat{\Omega}_1$ is equal to

$$P_e(\text{Single PU}) = \Pr(\hat{\Omega}_1 \neq \Omega_1 | X_2 \text{ is not transmitted}). \tag{2}$$

In the presence of the cognitive user, the symbol error probability is

$$P_e(\text{PU}) = \Pr(\hat{\Omega}_1 \neq \Omega_1 | X_2 \text{ is transmitted}). \tag{3}$$

Given the decision regions $\mathcal{B}_{\omega_{1,i}}$ of the PU's demodulator, the average symbol error probability can be calculated as

$$\begin{aligned} P_e(\text{PU}) &= 1 - \frac{1}{M_1}\sum_{i=1}^{M_1}\int_{\mathcal{B}_{\omega_{1,i}}} f_{Y_1|\Omega_1}(y_1|\omega_{1,i})\mathrm{d}y_1 \\ &= 1 - \underbrace{\frac{1}{M_1 M_2}\sum_{i=1,j=1}^{M_1,M_2}\int_{\mathcal{B}_{\omega_{1,i}}} f_{Y_1|\Omega_1,X_2}(y_1|\omega_{1,i},x_{2,ij})\mathrm{d}y_1}_{P_c(\text{PU})} \end{aligned} \tag{4}$$

where according to the complex Gaussian noise and additive channel

$$\begin{aligned} &f_{Y_1|\Omega_1,X_2}(y_1|\omega_{1,i},x_{2,ij}) \\ &\qquad = \frac{1}{2\pi\sigma_1^2}\exp\Big(-\frac{1}{2\sigma_1^2}|y_1 - x_{1,i} - \alpha x_{2,ij}|^2\Big). \end{aligned} \tag{5}$$

We assume that the transmitter of the CU is aware of the transmitted symbol of the PU in each channel use. The receiver of the CU, however, is not aware of this message but only a posterior Probability Mass Function (pmf) of the PU's modulation. The discrete random variable Ω_2 represents information messages of the CU and is defined uniformly over the set $\{\omega_{2,1},\ldots,\omega_{2,M_2}\}$. The modulator of the CU $\mathcal{F}_2 : \{\omega_{2,1},\ldots,\omega_{2,M_2}\} \times \mathbb{C} \to X_2 \in \mathbb{C}$ maps Ω_2 and the known transmitted signal from the PU (X_1) to the proper complex-valued signal X_2 which will be transmitted later. At the receiver of the CU, a complex Gaussian noise W_2 with mean zero and variance σ_2^2 is added to this signal. The received signal Y_2 is demodulated by demodulator function $\mathcal{G}_2 : Y_2 \in \mathbb{C} \to \{\omega_{2,1},\ldots,\omega_{2,M_2}\}$.

Using the *Standard Form* of cognitive radio channel [5], the direct channel gain between the transmitter and receiver of the CU is assumed to be one, and β is gain of the cross talk channel from the transmitter of PU to the CU's receiver. Thus, the received signal of the CU is $Y_2 = \mathcal{F}_2(\Omega_2, X_1) + W_2 + \beta X_1 = X_2 + W_2 + \beta X_1$. Based on the demodulation function $\mathcal{G}_2(Y_2) = \hat{\Omega}_2$, the average symbol error probability for the CU is $P_e(\text{CU}) = \Pr(\hat{\Omega}_2 \neq \Omega_2)$. For the given demodulator of the CU, decision regions $\mathcal{B}_{\omega_{2,j}}$ can be defined as

$$\mathcal{B}_{\omega_{2,j}} = \{y_2 | \mathcal{G}_2(y_2) = \omega_{2,j}\}, \quad j = \{1,\ldots,M_2\}. \tag{6}$$

$\mathcal{B}_{\omega_{2,j}}$ is a set of received signals y_2 which $\omega_{2,j}$ is the result of the CU's demodulator. The decision regions of the CU's demodulator are not fixed and can be changed adaptively according to the requirements. Based on these decision regions

$$P_e(\text{CU}) = 1 - \frac{1}{M_2}\sum_{j=1}^{M_2}\int_{\mathcal{B}_{\omega_{2,j}}} f_{Y_2|\Omega_2}(y_2|\omega_{2,j})\mathrm{d}y_2$$
$$= 1 - \underbrace{\frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}\int_{\mathcal{B}_{\omega_{2,j}}} f_{Y_2|\Omega_2,X_1}(y_2|\omega_{2,j},x_{1,i})\mathrm{d}y_2}_{P_c(\text{CU})}. \tag{7}$$

Where

$$f_{Y_2|\Omega_2,X_1}(y_2|\omega_{2,j},x_{1,i}) = \frac{1}{2\pi\sigma_2^2}\exp\Big(-\frac{1}{2\sigma_2^2}|y_2-\beta x_{1,i}-x_{2,ij}|^2\Big). \tag{8}$$

Along with the definition of the cognitive radio as a wireless device which can sense and adapt its transmission to the environment [3], $\mathcal{F}_2$ and $\mathcal{G}_2$ (and decision regions $\mathcal{B}_{\omega_{2,j}}$) can be designed based on different scenarios. As the CU is limited by its transmission power, we have a constraint on the power of its transmitted signal X_2.

$$E|X_2|^2 = \frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}|\mathcal{F}_2(\omega_{2,j},x_{1,i})|^2 = \frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}|x_{2,ij}|^2 \le P_{\text{CU}} \tag{9}$$

where P_{CU} is the maximum acceptable power for the CU's transmission.

III. Different Secondary Transmission Scenarios

Based on our definitions, three general cases can be assumed for uncoded secondary transmission in the AWGN channel: optimal cancellation, full relay and *Considerate* (combination of optimal cancellation and full relay methods). These cases are described as follows:

A. Optimal Cancellation

In this scenario, the CU is employing the optimal cancellation method introduced in [8] for cancelling the interference produced by the PU. Here, the focus is on maximization of the performance of the CU's link, and no concern is given to the possibly detrimental effects on the PU's performance. As mentioned before, our interferer is a user, and comparing to [8] which uses a continuous random variable for modeling the interference, we model it using a discrete random variable.

For design of the optimal modulator and demodulator pair, first it is assumed that the optimal modulator $\mathcal{F}_2$ is given and the decision regions for correct demodulation are defined based on the maximum likelihood rule.

$$\begin{aligned}\hat{\omega}_{2,j} =& \mathcal{G}_2(y_2)\\ =& \operatorname*{argmax}_{\omega_{2,j}\in\{\omega_{2,1},\ldots,\omega_{2,M_2}\}} f_{Y_2|\Omega_2}(y_2|\omega_{2,j})\\ =& \operatorname*{argmax}_{\omega_{2,j}\in\{\omega_{2,1},\ldots,\omega_{2,M_2}\}} \sum_{i=1}^{M_1}\Big\{\\ & \exp\Big(-\frac{1}{2\sigma_2^2}|y_2-\beta x_{1,i}-\mathcal{F}_2(\omega_{2,j},x_{1,i})|^2\Big)\Big\}.\end{aligned} \tag{10}$$

Now we assume the demodulator $\mathcal{G}_2$ is given and optimal modulator must be designed. Design of the modulator can be reformulated as an optimization problem. The aim of this optimization is maximization of the performance of CU's link with respect to the power constraint (9).

$$\text{Optimal Cancellation:}\begin{cases}\operatorname*{minimize}_{x_{2,ij}\in\mathbb{C}} P_e(\text{CU})\\ \text{subject to } E|X_2|^2 \le P_{\text{CU}}\end{cases} \tag{11}$$

For solving this optimization problem, the same as [8] a proper objective function is found using (7) and (9). Then, it is differentiated with respect to $x_{2,ij}$ and is set equal to zero. Using an iterative method, a nonlinear system of equations consisting of $M_1 \times M_2 + 1$ equations is solved for finding the transmitted signals of secondary user (cognitive user). For jointly designing of the optimal modulator and demodulator pair, after each iteration the decision regions are updated based on (10). Due to the space constraints we refer to [8] for more details on this iterative optimization method.

B. Full Relay

In this case, the CU is not concerned about its own transmission, and just helps the PU's transmission by relaying its messages. From another point of view, this is an optimization problem in which the proper transmission signals of the CU ($x_{2,ij}$) must be found to minimize the symbol error probability of the PU's link. Still the power constraint (9) must be considered.

$$\text{Full Relay:}\begin{cases}\operatorname*{minimize}_{x_{2,ij}\in\mathbb{C}} P_e(\text{PU})\\ \text{subject to } E|X_2|^2 \le P_{\text{CU}}\end{cases} \tag{12}$$

Minimization of $P_e(\text{PU})$ is the same as maximization of $P_c(\text{PU})$ defined in (4). Using (4), power constraint (9) and Lagrange multiplier λ_1, the objective function for finding a proper $x_{2,ij}$ can be written as

$$\frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}\Big\{\int_{\mathcal{B}_{\omega_{1,i}}} f_{Y_1|\Omega_1,X_2}(y_1|\omega_{1,i},x_{2,ij})\mathrm{d}y_1 - \lambda_1|x_{2,ij}|^2\Big\}. \tag{13}$$

Now to find the values of $x_{2,ij}$ which maximize the objecting function (13), (5) is used, derivatives are taken with respect to

$x_{2,ij}$ and the result is set equal to zero.

$$\frac{1}{2\pi\sigma_1^2}\frac{\alpha}{\sigma_1^2}\int_{\mathcal{B}_{\omega_{1,i}}}\Big\{ (y_1-x_{1,i}-\alpha x_{2,ij})\exp\Big(-\frac{1}{2\sigma_1^2}|y_1-x_{1,i}-\alpha x_{2,ij}|^2\Big)\Big\}\mathrm{d}y_1 = 2\lambda_1|x_{2,ij}|. \quad (14)$$

Using (14) with the power constraint (9), we have a nonlinear system of equations with $M_1 \times M_2 + 1$ equations and the same number of unknown variables (λ_1 and $x_{2,ij}$). We suggest a fixed point iteration method for solving the system. Using an initial value for $x_{2,ij}$ we calculate the left hand side of (14). Current value of λ_1 is found using the power constraint (9) and current values of $x_{2,ij}$. Left hand side of (14) is divided by $2\lambda_1$ and current value for $x_{2,ij}$ is found. This algorithm is repeated until it converges. In general, the information messages of the CU (Ω_2) is independent of the PU messages (Ω_1). Thus, the transmitted signals of CU (X_2) in this scenario are only functions of PU's transmitted signals (X_1). CU in this scenario is selfless and designing a demodulator for it is meaningless. The symbol error probability of the PU in this case is a lower bound for any other case (one-dimensional case) where the CU is also available.

C. Considerate

None of the two previous scenarios can fulfill the coexistence conditions. Thus, *a proper combination of the Optimal Cancellation and Full Relay* must be used. Similar to the selfish scenario, in order to design the optimal modulator and demodulator jointly we split the procedure in two steps of designing the demodulator for a given modulator and vice versa. In this case, the performance of the CU should be maximized (minimizing the symbol probability of error). In addition to the power constraint for CU's transmission, another constraint must be added to the optimization to guarantee the performance of the PU's link. This new constraint can be formed by comparing the performance of the PU in absence of the CU with the case where the CU is also available. Therefore, the optimization can be written as

$$\begin{aligned}&\underset{x_{2,ij}\in\mathbb{C}}{\text{minimize}}\ P_e(\text{CU})\\ &\text{subject to}\ \begin{cases}P_e(\text{PU}) = P_e(\text{Single PU})\\ E|X_2|^2 \le P_{\text{CU}}\end{cases}\end{aligned} \quad (15)$$

The objective function which must be maximized is written using equations (4), (7) and two Lagrange multipliers λ_1 and λ_2 for including the CU's power constraint (9), and PU's performance constraint as

$$\frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}\Big\{\int_{\mathcal{B}_{\omega_{2,j}}} f_{Y_2|\Omega_2,X_1}(y_2|\omega_{2,j},x_{1,i})\mathrm{d}y_2 - \lambda_1\int_{\mathcal{B}_{\omega_{1,i}}} f_{Y_1|\Omega_1,X_2}(y_1|\omega_{1,i},x_{2,ij})\mathrm{d}y_1 - \lambda_2|x_{2,ij}|^2\Big\}. \quad (16)$$

By taking derivatives of (16) in respect to $x_{2,ij}$ we have

$$\begin{aligned}&\underbrace{\frac{\partial P_c(\text{CU})}{\partial x_{2,ij}}}_{K_{ij}} - \lambda_1\underbrace{\frac{\partial P_c(\text{PU})}{\partial x_{2,ij}}}_{L_{ij}} - \lambda_2\underbrace{\frac{\partial P_{\text{CU}}}{\partial x_{2,ij}}}_{2x_{2,ij}}\\ &= \frac{1}{2\pi\sigma_2^2}\frac{1}{\sigma_2^2}\int_{\mathcal{B}_{\omega_{2,j}}}\Big\{ (y_2-\beta x_{1,i}-x_{2,ij})\exp\Big(-\frac{1}{2\sigma_2^2}|y_2-\beta x_{1,i}-x_{2,ij}|^2\Big)\Big\}\mathrm{d}y_2\\ &- \lambda_1\frac{1}{2\pi\sigma_1^2}\frac{\alpha}{\sigma_1^2}\int_{\mathcal{B}_{\omega_{1,i}}}\Big\{ (y_1-x_{1,i}-\alpha x_{2,ij})\exp\Big(-\frac{1}{2\sigma_1^2}|y_1-x_{1,i}-\alpha x_{2,ij}|^2\Big)\Big\}\mathrm{d}y_1\\ &- 2\lambda_2|x_{2,ij}|.\end{aligned} \quad (17)$$

Setting (17) equal to zero and using two discussed constraints, we have a system of $M_1 \times M_2 + 2$ nonlinear equations and the same number of unknown variables ($x_{2,ij}$, λ_1 and λ_2). The method of solving this nonlinear system of equations and designing the modulator and demodulator pair jointly is discussed in the next section. Exploiting the *considerate method*, the coexistence conditions of our uncoded cognitive radio channel can be fulfilled.

IV. Implementation And Numerical Results

A. Implementation Of the Considerate Method

For the joint optimization of the modulator and demodulator of the CU, we have used a variation of the iterative method used in [8]. Setting (17) equal to zero, dividing both sides by $2\lambda_2$, and renaming $\frac{1}{2\lambda_2} \to \lambda_3$ and $\frac{-\lambda_1}{2\lambda_2} \to \lambda_4$ we have

$$\lambda_3 K_{ij} + \lambda_4 L_{ij} = x_{2,ij}. \quad (18)$$

Solving (18) along with the constraints in (15) leads to the proper solution for this scenario. The two constraints can be written as

$$\frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}\int_{\mathcal{B}_{\omega_{1,i}}}\Big\{ \exp\Big(-\frac{1}{2\sigma_1^2}|y_1-x_{1,i}-\alpha(\lambda_3K_{ij}+\lambda_4L_{ij})|^2\Big)\Big\}\mathrm{d}y_1 = P_e(\text{Single PU}), \quad (19a)$$

$$\frac{1}{M_1M_2}\sum_{i=1,j=1}^{M_1,M_2}|\lambda_3K_{ij}+\lambda_4L_{ij}|^2 \le P_{\text{CU}}. \quad (19b)$$

Using the fixed point iteration and the definitions above we propose the following steps:

1) Start from a proper initial point $x_{2,ij}$ and its corresponding decision region $\mathcal{B}_{\omega_{2,j}}$. This can be, for example, the original constellation points and the decision regions of a single user case.
2) K_{ij} and L_{ij} are calculated using the current $x_{2,ij}$. Substituting these values in (19a) and (19b), a system of

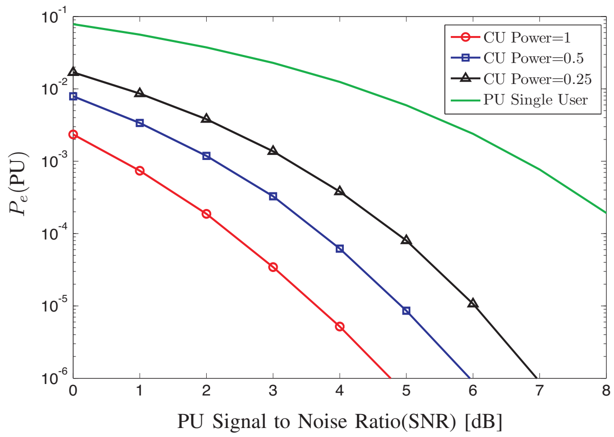

Fig. 2: Performance of PU using the full relay method vs. PU SNR. $\alpha = 1$, $\beta = 1$ and Power of PU=1.

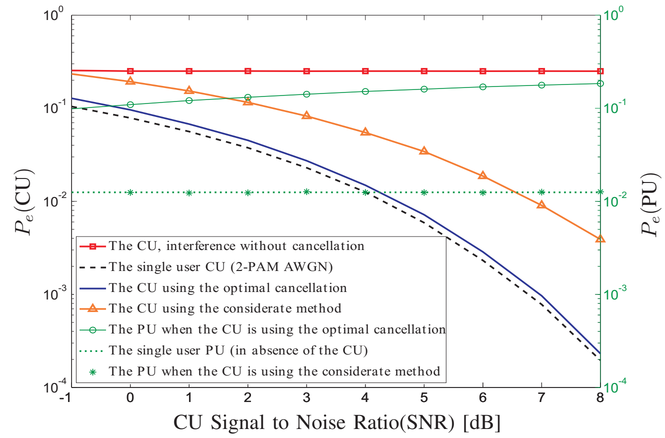

Fig. 3: Performance of PU and CU in different scenarios vs. CU SNR. In all cases $\alpha = 1$, $\beta = 1$, Transmission Power of CU=1, Transmission Power of PU=1 and SNR of PU= 4 dB.

two nonlinear equations is constructed. In this system λ_3 and λ_4 are the unknown variables to be found. Another iterative method such as Newton's method is suggested for solving this system.

3) After solving the system (19a) and (19b), the left hand side of (18) is calculated using the current values of λ_3, λ_4, K_{ij} and L_{ij}. The result is the updated value of $x_{2,ij}$.
4) The decision regions $\mathcal{B}_{\omega_{2,j}}$ are updated using the new value of $x_{2,ij}$ and the likelihood function (10). If the difference of the current and the previous value of $x_{2,ij}$ is larger than a threshold we go to Step 2 and start another iteration with the current values. Otherwise, the algorithm is converged.

B. Numerical Results

The simulation setup and the results presented here are based on the system model discussed in Section II (Figure 1). In our simulations, both PU and CU have two information messages ($M_1 = 2, M_2 = 2$). The PU uses binary Pulse Amplitude Modulation (2-PAM). In the full relay scenario, the CU also uses a two-point constellation corresponding to the PU's transmitted signals, regardless of its own information messages Ω_2. In the two other scenarios, the CU needs to use a four-point constellation corresponding to each combination of PU's transmitted signals X_1 and its own information messages Ω_2. The designed modulator and demodulator pairs of the discussed scenarios are evaluated for different values of signal and noise power in the PU and CU's links. The Monte Carlo simulation method is used to compute the performance of each case.

The performance evaluation results of the PU's link corresponding to the full relay scenario are illustrated in Figure 2. The CU behaves as a relay and spends all of its transmission power to help the PU's link. It can be seen that the more power the CU is allowed to use; the better performance is achievable in the PU's link.

Figure 3 compares the performance of CU in different scenarios. In addition, the effects of using the optimal cancellation method and considerate case on the performance of the PU

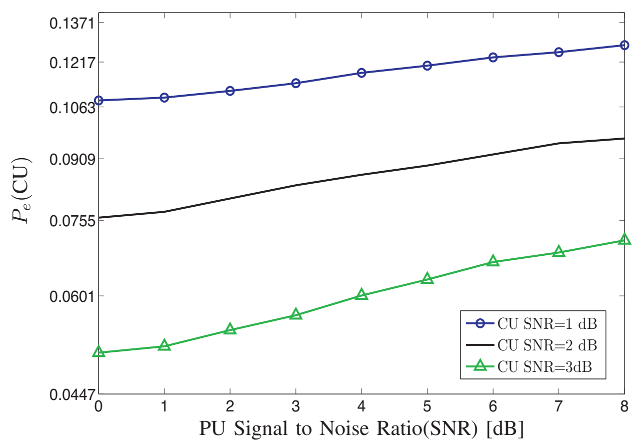

Fig. 4: Performance of CU using the considerate method vs. PU SNR. $\alpha = 1$, $\beta = 1$, Transmission Power of CU=1 and Transmission Power of PU=1.

link are shown in this figure. Here, the PU link has a constant SNR and consequently a certain symbol error probability. Using the optimal cancellation method, CU cancels out a large portion of interference and its symbol error probability is close to the case in which there is no interference. But as it is mentioned before, the performance of PU link is degraded and its probability of error is increased. It can be seen that the CU in *considerate* scenario performs much better than the interference case (interference without cancellation). On the other hand, the performance of the CU's link is degraded compared to the optimal cancellation case. However, this degradation is the result of the same symbol error probability for the PU's link before and after presence of the CU.

Figure 4 depicts results of exploiting the *considerate* method for different SNRs of the PU's link (different P_e(Single PU)). Generally, all three curves in this figure show that increasing the SNR of the PU's link decreases the performance of the CU's link. Increasing the SNR of the PU is the same as improving its performance (decreasing the P_e(Single PU)). Therefore, the CU must care more about the PU's link compared to its own link. Thus, the selfless side of the method is dominant compared to the selfishness. Another effect that can be seen in Figure 4 is the improved performance of the CU's link with increased SNR. This result was expected, and is the same in any other communication link.

V. Further Discussion

Observing the information of the primary user messages beforehand is an important issue. There are some practical solutions for this problem. For example, it can be assumed that the transmitters of the primary and cognitive user are two base stations which have a high capacity and instantaneous link between. As a result, the transmitted sequences of the primary user can be available for the cognitive user's transmitter in advance. Another scenario is assuming that the two transmitters are closer to each other physically compared to the distance between the transmitter and receiver of the primary user. In this case, generally the SNR of the wireless channel between the transmitters is more than the SNR of the link between the transmitter of the primary user and its receiver. Thus, the transmitter of cognitive user can decode the transmitted messages of the primary user in fewer channel uses, compared to what the primary user receiver needs for decoding. Therefore, cognitive user can listen to the primary user's link and after decoding a part of transmitted sequence acquires the upcoming part of it beforehand.

VI. Conclusion

Three different scenarios for designing the modulator and demodulator of the cognitive user for an uncoded cognitive transmission (secondary user transmission) and their implementation methods have been studied in this paper. The *considerate method* is the most appropriate scheme which can fulfill the requirements of the real cognitive radio channels. Using this method, the cognitive user improves the performance of its own link as much as possible on the promise of no degradation on the quality of the primary user's link. Comparing the symbol error probability, it can be seen that the performance of the cognitive user is much better than the interference case. However, the cognitive user's performance is degraded compared to the optimal cancellation method. But as its presence is not harmful for primary user's communication, it can communicate in the same frequency band as the primary (licensed) user of the band. Note that this system is an uncoded cognitive radio channel. Therefore, without changing the method, it can be connected to an outer channel coding for increasing the performance of the cognitive user's link.

The approaches used in the considerate method -the symbol by symbol strategy for an uncoded channel and the constraint of symbol error probability of the primary user link- can be used as a low complexity practical solution for the secondary spectrum licensing and increase the spectral efficiency.

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References

[1] US, "Federal communications commission, spectrum policy task force report," *ET Docket*, pp. 02–135, 2002.

[2] *Federal Communications Commission, Cognitive Radio Technologies Proceeding (CRTP), ET Docket*, no. 03-108, 2003, [Online]. Available: http://www.fcc.gov/oet/cognitiveradio/.

[3] I. Mitola, J., "Software radios: Survey, critical evaluation and future directions," *Aerospace and Electronic Systems Magazine, IEEE*, vol. 8, no. 4, pp. 25 –36, apr 1993.

[4] N. Devroye, P. Mitran, and V. Tarokh, "Achievable rates in cognitive radio channels," *Information Theory, IEEE Transactions on*, vol. 52, no. 5, pp. 1813 – 1827, may 2006.

[5] A. Jovicic and P. Viswanath, "Cognitive radio: An information-theoretic perspective," *Information Theory, IEEE Transactions on*, vol. 55, no. 9, pp. 3945 –3958, sept. 2009.

[6] M. Costa, "Writing on dirty paper (corresp.)," *Information Theory, IEEE Transactions on*, vol. 29, no. 3, pp. 439 – 441, may 1983.

[7] N. Devroye, P. Mitran, and V. Tarokh, "Limits on communications in a cognitive radio channel," *Communications Magazine, IEEE*, vol. 44, no. 6, pp. 44 –49, june 2006.

[8] M. Skoglund and E. Larsson, "Optimal modulation for known interference," *Communications, IEEE Transactions on*, vol. 56, no. 11, pp. 1892 –1899, november 2008.