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Maximizing the minimum achievable rates in Cognitive Radio networks subject to stochastic constraints

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ABSTRACT

In this paper, considering errors in estimating the channel state information (CSI), we investigate the problem of robust beamforming in cognitive radio (CR) networks to maximize the minimum achievable rates for secondary users (SU). In addition to the constraints on the transmit power of the users, stochastic constraints on the signal to interference plus noise ratio (SINR) at SUs and interference power at the primary users (PU) are imposed to guarantee the quality of service (QoS) of the network. Bernstein inequalities and semi-definite relaxation are used to transform stochastic constraints to equivalent deterministic inequalities. By replacing new deterministic constraints in the optimization problem and defining new matrices, we write the problem of finding optimal beamforming weights in the form of quasiconvex optimization problem. Generalization of the Dinkelbach's method is used to obtain optimal beamforming weights. Also, the problem of finding optimum beamforming weights is solved for the case that perfect CSI is available at the transmitters. Simulation results confirm that, the proposed method provides higher achievable rates in comparison with the previous works that minimize the total transmit power. The proposed method is robust because stochastic constraints are satisfied while the estimation of CSI includes some errors.

1. Introduction

Frequency spectrum scarcity becomes a serious challenge for future telecommunication systems. Cognitive radio (CR) networks have been introduced to reuse the frequency resources of the primary users (PU). In CR networks which was first introduced by [1], secondary users (SU) get permission to use the licensed spectrum till the induced interferences on the primary receivers kept below the predefined threshold [2,3].

Due to spatial filtering, deploying arrays in underlay CR has been considered extensively [4–7]. By choosing the transmit/receive beamforming vectors intelligently, interferences on the primary receivers are controlled, and consequently SUs can access the leased frequency spectrum simultaneously. Different criteria are introduced to choose the optimum transmit beamforming weights. In some papers, the objective function is maximizing the achievable rates for SUs and constraints are imposed to control interferences on the PUs. Also, signal to interference plus noise ratio (SINR) constraints may be considered to guarantee the quality of service (QoS) in each user. Some other papers consider the minimum transmit power in SUs as the objective function. Constraints on the interference at PUs and minimum SINR at SUs are imposed to ensure that each user achieves the minimum QoS.

One of the limiting factors in beamforming techniques is the inaccuracy in the channel state information (CSI), which happens frequently in practical applications. To solve this problem, some robust beamforming methods for CR networks are proposed [8–11]. The problem of maximizing the minimum SINR in SUs has been considered in [8] for a CR network with one secondary transmitter, M secondary receivers, and L primary receivers. Constraints on the transmit power, interference at the primary receivers, and SINR on the secondary receivers are imposed to guarantee the QoS in the network. Estimation error of the CSI is assumed to belong to ellipsoid set with known parameters. The problem of maximizing the minimum received SINR in a downlink communication system is considered in [12] in the case that perfect CSI is available at the transmitter. Constraint on the transmit power of each user is imposed. Since there is not any constraint on the interference power at the users, method [12] could not be deployed for CR networks. Also, performance of this method decreases in the case of having uncertainties in the CSI. In [8], the problem of finding optimal beamforming weights is solved in the worst-case scenario. Using theorems and lemmas in linear algebra, the non-convex problem of finding optimum beamforming weights is converted to a semi-definite convex programming problem only in the single transmitter networks. The results of [8] cannot be applied to networks with several secondary

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transmitters. Authors in [9] consider a CR network with a secondary receiver-transmitter pair and a primary receiver. The estimation of CSI from secondary transmitter to primary receiver is assumed to be included with some errors. Considering ellipsoid set to cover all possible choices of error in estimating CSI, the signal covariance matrix is chosen such that the rate of the SU is maximized while the interference power at the PU is kept below a threshold. Similar to [8], method [9] could not be used in networks with several secondary transmitters. In [10], the CSI estimation error is modeled by Gaussian vector with zero mean and known covariance matrix. Transmit powers by SUs are minimized subject to stochastic constraints on the interference power at the primary receiver and SUs' SINR. SINR at the receivers and consequently achievable rates of the users are not included in the objective function of the method [10]. Therefore, this method is not optimum in the viewpoint of achievable rates for the users.

In this paper, considering estimation error of the CSI, we investigate the problem of robust beamforming in CR networks with arbitrary number of users. The problem of maximizing the minimum achievable rates of the users in non CR networks with constraints on the SINR of the users could be found in papers [13–15]. The same objective function is considered in this paper for CR networks. We maximize the minimum achievable rates for the SUs subject to stochastic constraints on the interference power at the primary receiver and SINR on the SUs. Also, constraints on the transmit power of the SUs are considered. In practical applications, maximum transmit power of each user is limited. So, in comparison with [10], simultaneously guarantying the QoS of the users and satisfying constraints on the transmit power is more practical in telecommunication networks. Similar to the most CR networks, PUs choose their transmit parameters regardless of the activity of SUs. To avoid confusing the reader, only a single PU is considered in the system modeling. The presented method is generalized in Appendix A to the case that more PUs exist in the network. Since we consider several secondary transmitters and receivers in the network, different approach from those presented in [9,8] is introduced to convert the non-convex problem of finding optimum beamforming weights to an equivalent relaxed quasiconvex optimization problem. Finally, we propose an algorithm to reach the optimal solution of the relaxed optimization problem. Simulation results show that the stochastic SINR and interference constraints are satisfied by the optimal beamforming weights obtained by the proposed algorithm. Robustness of the proposed method is confirmed by the results obtained in the case that CSI is estimated with error.

The remaining parts of the paper are organized as follows: system modeling is given in Section 2. In Section 3, stochastic constraints are transformed to equivalent deterministic constraints. Using methods to solve general fractional programming, an algorithm is proposed in Section 4 to obtain optimum beamforming weights. In Section 5, the beamforming problem is investigated in the case of having perfect CSI at the secondary transmitters. In Section 6, simulation results are given to validate performance of the proposed method. Finally, conclusions are drawn in Section 7.

Vectors and matrices are denoted by boldface lowercase and boldface uppercase letters respectively. The superscript $(.)^H$ denotes the conjugate transpose, and $(.)^T$ denotes the transpose. Tr(.) indicates the trace of a matrix. $\mathbf{I}_N$ denoted the $N \times N$ identity matrix.

2. System model

Consider a CR network consisting a single PU and s SU transmitter/receiver pairs as shown in Fig. 1. The case of having multiple PUs is considered in Appendix A. The multiple input single output (MISO) structure with N_t antennas at the transmitter side is considered in both PU and SUs. We consider narrowband transmission for both PU and SUs in which all users share the same bandwidth in an overlay CR network.

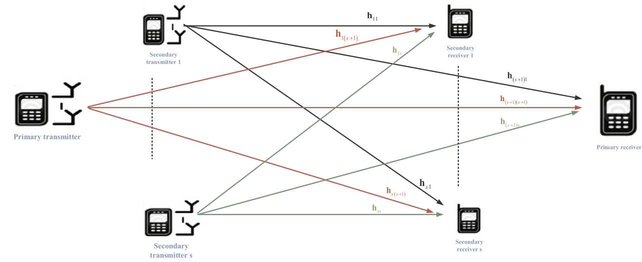

Fig. 1. Cognitive radio network with one primary and s secondary users.

As shown in Fig. 1, $\mathbf{h}_{ij} \in \mathbb{C}^{N_t \times 1}$ denotes the channel coefficients from the jth transmitter to the ith receiver. All entries of channel coefficients are assumed to be independent from each other and remain constant in each time slot. To avoid complexity in the notation, the PU is shown as the $(s + 1)$th user. Since PU is the owner of the frequency spectrum, primary network parameters are pre-designed regardless of the interference on the SUs. A fixed weight $\mathbf{v}$ is used to show the primary beamforming vector. The signal received at the ith secondary receiver can be expressed as follows:

$$r_i = \mathbf{h}_{ii}^H \mathbf{w}_i s_i + \sum_{j \neq i}^{s} \mathbf{h}_{ij}^H \mathbf{w}_j s_j + \mathbf{h}_{i(s+1)}^H \mathbf{v} s_{s+1} + n_i, \quad i = 1,\ldots,s \tag{1}$$

where s_i is the transmitted signal with unit energy from the ith user. We do not pose any restriction on the type of the transmitted signals. $\mathbf{w}_i \in \mathbb{C}^{N_t \times 1}$ is the beamforming vector at the ith transmitter. n_i is the noise on the ith receiver which is modeled as white Gaussian random variable with zero mean and variance σ_i^2. Noise in each receiver is independent from all transmitted signals and received noise on the other users. In the similar manner, signal on the primary receiver is given in the following form:

$$r_{s+1} = \mathbf{h}_{(s+1)(s+1)}^H \mathbf{v} s_{s+1} + \sum_{j=1}^{s} \mathbf{h}_{(s+1)j}^H \mathbf{w}_j s_j + n_{s+1} \tag{2}$$

Although, the estimation of CSI from secondary transmitters to secondary receivers are not challenging, we confront much difficulty in estimating the CSI from secondary transmitters to primary receivers in CR networks. One possible scenario for the estimation is that the PU systems are time division duplex (TDD) and both the primary and secondary users share the same frequency band. In this scenario, the secondary transmitters sense the transmitted signal by the primary receiver. Knowing the pilot symbols transmitted by primary receivers, the secondary transmitters estimate CSI to receivers [16–18]. The cooperation of PUs with the SUs in the estimation of CSI could be found in [19–21].

To have a general model, we consider random vector for the estimation error of the CSI in each links. Each error is modeled by Gaussian vector with zero mean and known covariance matrix.The CSI from the jth transmitter to the ith receiver is modeled as follows:

$$\mathbf{h}_{ij} = \widehat{\mathbf{h}}_{ij} + \delta \mathbf{h}_{ij} \tag{3}$$

where $\mathbf{h}_{ij} \in \mathbb{C}^{N_t \times 1}$ is the actual vector channel coefficients from the jth transmitter to the ith receiver which cannot be estimated exactly. $\widehat{\mathbf{h}}_{ij} \in \mathbb{C}^{N_t \times 1}$ is the estimated CSI, and $\delta \mathbf{h}_{ij} \in \mathbb{C}^{N_t \times 1}$ is the error in estimating that vector coefficients. Estimation error of the CSI for different links are modeled by independent random vectors. Each $\delta \mathbf{h}_{ij}$ is modeled as zero mean Gaussian random vector with covariance matrix $\mathbf{E}_{ij} \in \mathbb{R}^{N_t \times N_t}$. The matrix $\mathbf{E}_{ij}$ characterizes the estimation error of the CSI from the ith transmitter to the jth receiver. Using (2) and considering $\mathbf{h}_{lj}$ in (3) as the channel coefficients from jth transmitter to the lth receiver, total interference power at the primary receiver caused by SUs is