Joint Detection and User Selection Algorithms in Cognitive Wireless Communication System

Fazhong Liu, Mingming Li, Lizhu Zhai, and Chong Li

***Abstract*—Cognitive wireless networks usually utilize large numbers of cognitive nodes to collect cognitive information of the authorized frequency bands and do automatic configuration to finish spectrum sharing processes. How to realize joint detection and choose appropriate cognitive nodes to achieve opportunity type spectrum access should be considered in a cognitive wireless communication system. In this paper, we present a joint detection algorithm to finish cognitive information collection and one user selection scheme to minimize co-channel interference for the downlink of a cognitive mesh network with the coexistence of many primary nodes and cognitive nodes. In the joint detection strategy, the central node controls more than one cognitive user to jointly detect the primary channel. While the effective user selection algorithm is proposed to choose a group of cognitive nodes while maximizing the sum rate of primary nodes and satisfying the co-channel interference constraint from the cognitive nodes to primary nodes, meanwhile, the total transmitted power constraint for primary access point (PAP) as well as the Signal to Interference and Noise Ratio of the cognitive nodes is bigger than a given threshold γ. Simulation results show that our suboptimal algorithm is able to achieve high sum rate throughput with low complexity.**

***Index Terms*—Co-channel interference, cognitive wireless communication, joint detection, user selection.**

I. Introduction

Cognitive informatics (CI) has been developed fast recently. Wang had mentioned one theoretical architecture of contemporary cybernetics and cognitive informatics and a cognitive machine with CI ideas [1]. Lots of orgnizations had claimed that the ever fixed spectrum allocation methods leads to vast spatial variations in the usage of allocated spectrum such as Federal Communications Commission (FCC). This motivates the concepts of cognitive radio which was regarded as a promising technology to utilize licensed bands by enabling cognitive nodes to share the spectrum allocated for primary nodes [2]. Spectrum sensing, spectrum management, spectrum mobility and spectrum sharing are the main research fields about cognitive radio technology. With the conception of CI, it is a paradigm of cognitive informatics and computational intelligence. However, in a cognitive wireless communication system, how to realize joint detection and choose appropriate cognitive nodes to achieve interference reduction caused by cognitive nodes have become obstacles to primary nodes which limits its system performance. To cognitive wireless communication designers, they had better try to find new schemes to increase primary nodes throughput while protecting cognitive nodes can make opportunity type spectrum accesses. The authors in this paper want to lay multiple antennas at the PAP as transmitting antennas with the aims to increase system rates and diminish their transmitting times. The system figure is depicted is Fig 1 and model is made in Section two.

Spectrum sensing is needed in cognitive wireless network as cognitive nodes are the second users who must detect the licensed frequency band to find free time slots for transmitting without too much interference to the primary users in such a network [3]. Being different from the distributed structure, The centrally-controlled cognitive wireless network like Fig 1 has a central access point will control network resources and designate all cognitive users to access the primary spectrum orderly. Then in a centrolly-controlled cognitive radio network, cognitive users candetect spectrum usage with some prior knowledges of modulation format and characteristics about primary network, such as the bandwidth, carrier frequency, and chip-rate. The most difficult thing do finish spectrum sensing in such a network structure is that how to generate a global spectrum usage decision given a set of decision rules in local detection nodes. The authors in this paper focus on how to do joint detection of a centrally-controlled wireless network with a decision set P and then we give out how to do user selection while maximizing the sum rate of primary nodes and satisfying the co-channel interference constraint from the cognitive nodes to primary nodes, meanwhile, the total transmitted power constraint for primary access point (PAP) as well as the Signal to Interference and Noise Ratio of the cognitive nodes is bigger than a given threshold γ.

Referring to user selection combined with system permormance estimating, many studies focus on the performances of cognitive wireless communication systems have been shown in [4-6], but little paper dabbles in primary nodes purposefully decrease co-channel interference caused by cognitive nodes. Mingguang Xu and Dong Lin (2006) present game theory to handle the resource allocating

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problem between cognitive users to achieve maximum rate [4]. The representative contributions to cognitive MIMO system are mainly detailed in [6], which focognitive nodes ed on joint utilization between beam forming, scheduling, and antenna selection in cognitive MIMO system. In [7], the writers pointed out that the beamforming algorithm has been also exploited as a strategy that can serve many users at similar throughput but with lower complexity than DPC. Then in this article, we consider a MIMO system with the coexistence between a set of primary users and a cognitive user and try to find out an active beamforming technique for Primary nodes to enlarge Primary nodes ' sum throughput. Meanwhile, we propose to decrease the co-channel interference constraint from the CU to Primary nodes with the total transmitted power constraint for PAP. To simplify the sum rate maximization problem, one suboptimal precoding scheme is proposed to remove the co-channel interference from cognitive network to Primary nodes completely as well as mitigate interference between Primary nodes .

The remainder of this paper is organized as follows. In Section II, we give the system model and formulate the problem of sum rate maximization. In Section III, we propose joint detection strategy of a Centrally-controlled cognitive wireless network. The algorithm CR-SUS and power allocation scheme are elaborated in Section IV. Numerical and computer simulation results are presented in Section V. Finally, the last section draws the conclusions of the paper. We adopt the following notional convention: an identity matrix of size $N \times N$ is expressed by I_N, the operators $(\cdot)^{\mathrm{H}}$ and $(\cdot)^{+}$ denote conjugate transpose and pseudo-inverse operation.

II. System Model and Problem Formulation

As described in previous spectrum sharing studies [4] and [6], we assume that a dual system with one primary access point decreases interference from the *M* cognitive nodes at *K* primary receivers drawn in Fig 1. The PAP is equipped with N_p transmit antennas, the *j*-th PU is uniformly spaced only with one antenna ($j = 1, 2, \ldots K$, $K \gg N_p$), and the cognitive access point (CAP) is equipped with N_c transmit antennas while the *i*-th cognitive node is played with a single received antenna ($i = 1, 2, \ldots M$, $M \gg N_c$). The received signal vectors at the *i*-th cognitive receiver and the *j*-th primary receivers, y_{ci} and y_{pj} , are given respectively as

$$y_{ci} = \sum_{i=1}^{M} h_{ci} w_{ci} x_{ci} + \sum_{j=1}^{k} h_{ci} w_{pj} x_{pj} + w_c$$

and $y_{pj} = \sum_{i=1}^{k} h_{pj} w_{pi} x_{pi} + w_{pj}$, where $h_{ci} \in C^{1\times N_p}$ is the channel between the PAP and the *i*-th cognitive node , $h_{pj} \in C^{1\times N_p}$ is the channel between PAP and the *j*-th primary node, x_c and x_{pj} denote transmitting signals, modulation matrixes $W_c = \{W_{c1}, W_{c2} \ldots W_{cM}\}$ and $W_p = \{W_{p1}, W_{p2} \ldots W_{pk}\}$ are introduced to eliminate interference to primary nodes caused by cognitive nodes and multiple user interference among Primary nodes as well as w_c (1×1) and w_{pj} (1×1) are Gaussian noise vector independent with zero mean and variance σ_0^2 and σ_{pj}^2 respectively, for all j in 1 to k. To maximize the sum rate of primary nodes satisfying the condition that the co-channel interference received by primary nodes under a tolerable threshold ς_p , the sum of transmitting power for all primary nodes at PAP is constrained with total power P_P , and the $SINR_c$ is larger than the value γ . Then optimization problem in the downlink channel of the cognitive wireless communication system with M cognitive user can be expressed as

$$R_p = \max_{P,\, W} \sum_{j=1}^{k} \log_2 \det\Big(I + \frac{h_{pj} W_{pj} P_{pj} W_{pj}{}^{H} h_{pj}{}^{H}}{\sigma^2 I + \sum_{i \neq j} h_{pj} W_{pi} P_{pi} W_{pi}{}^{H} h_{jj}{}^{H}}\Big) \quad (1)$$

$$\text{s.t.} \quad \sum_{j=1}^{k} h_c W_{pj} P_{pj} W_{pj}^{\mathrm{H}} h_c^{\mathrm{H}} \le \varsigma_p$$

$$\sum_{j=1}^{k} P_{pj} \le P_P$$

$$\frac{|g_c|^2 P_c}{\sum_{j \neq k} |h_{pk} W_{pj}|^2 P_{pj} + |h_c|^2 P_P + \sigma_{pk}^2} > \gamma$$

In the upper equation, the first constrain is interference constrain to the *j*-th primary node, the second one is transmitting power constrain at the PAP, and the last one is $SINR_c$ constrain.

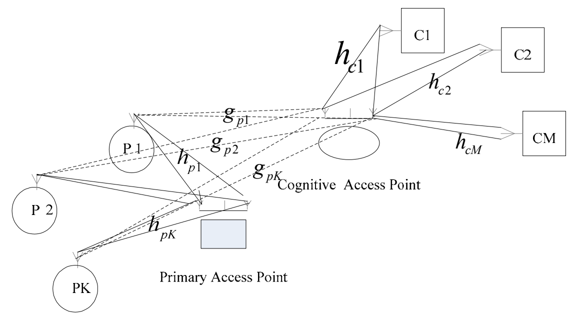

Fig.1. A Centrally-controlled cognitive wireless communication system

III. Joint Detection Strategy

Overlay and underlay are two main methods of access model used in wireless mesh network structure [8] [9]. Overlay type access method is simple in achieving the spectrum, because the cognitive nodes don't care the specific users channel state information, just to test whether the authorized users have taken up frequency band. Then the cognitive user's testing algorithms usually have smaller complexity. Compared with overlay pattern, underlay type spectrum access is relatively complicated, with the main reason is the cognitive link should realize the main user receivers can handle the number of interference. Then the complexity of the detection requirements is high. Firstly we consider the Fig1 which shows the centrally-controlled cognitive wireless network structure. In this system the cognitive access point can control cognitive nodes to detect which channel in the perception stage. When cognitive information is gathered, each local cognitive result will be collected and transmitted to the cognitive access point. Then the controlled point will judge which time slot is occupied according to the cooperation detection judging rules and use other related information to allocate the primary white time slots and return the results back to cognitive nodes.

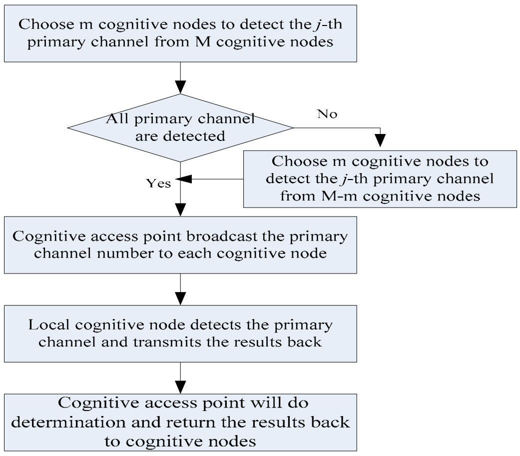

Fig.2. Joint detection strategy in centrally-controlled cognitive network

In the upper process, multiple cognitive nodes should be randomly chosen to make detection for the j-th primary channel with a group rules P. We can work out the missed detection probability p_f to the j-th primary channel with the following theorem.

Theorem 1:

Given the i-th cognitive node judges the j-th primary channel white with probability p_i and m cognitive nodes with probability $E\{p_j\}$, the i-th cognitive node judges the j-th primary channel is nearly white with probability as

$$p_{fj} = \frac{p_i + \sqrt[n]{E\{p_j\}[1-(1-p_j)^n] + (1-p_j)^n} - 1}{p_i}$$

Proof:

If we give out whether one primary channel is white or not with probability P, then k cognitive nodes cooperatively detect the e j-th primary channel is white or not with probability $\binom{n}{k_i} p_j^{k_i}(1-p_j)^{n-k_i}$. Then

$$E\{p_j\} = \frac{\sum_{k_i} p_{fj}^{k_i}\binom{n}{k_i} p_i^{k_i}(1-p_j)^{n-k_i}}{1-(1-p_j)^n}$$

$$\Leftrightarrow \sum_{k_i} p_{fj}^{k_i}\binom{n}{k_i} p_i^{k_i}(1-p_j)^{n-k_i} = E\{p_j\}[1-(1-p_j)^n]$$

$$\Rightarrow E\{p_j\} = \frac{\sum_{k_i}\binom{n}{k_i}(p_{fj}p_i)_j^{k_i}(1-p_j)^{n-k_i}}{1-(1-p_j)^n} = \frac{(p_{fj}p_i + 1 - p_i)^n - (1-p_j)^n}{1-(1-p_j)^n}$$

IV. CR-SUS Algorithm

Analyzing (1), the optimal problem has shown that we have to maximize the sum rate of primary nodes while make the cognitive nodes are transparent to primary nodes when it accesses the primary spectrum. Then a good choice of minimizing interference is providing a good zero forcing method to make the cognitive nodes as a special user and pre-cancel its interference to primary nodes firstly. As mentioned in [10], one way to accomplish this is to use dirty paper coding (DPC), which is a capacity achieving and theoretically optimal technique that can transmit signal transparently through the interference. Yet DPC is difficult to implement in practical systems due to its high complexity in successive encodings and decodings, especially when there are too much users in the system. Now we check the optimal problem in equation (1) again. Power P_p can be modulated with transmitting signals, and $SINR_c$ can be enlarged by increasing cognitive transmitting power P_c or decreasing primary power P_p . But increasing cognitive transmitting power P_c or decreasing primary power P_p will be a contradiction to the first constrain in (1) and to the main maximal problem. There must be a balance point within this question and it is not so difficult to work out the maximal problem is non-convex. Then we choose a design for the purpose of deriving the feasible solution to the question.

One method in judging two vectors are orthogonal or not is whether its inner product is zero, and the basic way to work out the standardization orthogonal basis $u_1, u_2 ....$ for a group of vectors $v_1, v_2 .... v_k$ (with full rank), is

$$u_k = v_k - \sum_{j=1}^{k-1}\frac{v_k u_j^{\mathrm{H}}}{\left\|u_j\right\|^2}u_j = v_k\left(I - \sum_{j=1}^{k-1}\frac{u_j^{\mathrm{H}} u_j}{\left\|u_j\right\|^2}\right) \tag{2}$$

Using (2), we obtain the two phase algorithm as the following

Step one:

1) Find out the orthogonal user for the cognitive nodes in the group of primary nodes, if there are not enough primary nodes in the group who are orthogonal to the cognitive nodes, we choose to find the near orthogonal primary nodes for the cognitive nodes. We mark this assembly as T_p and make sure of the value $|T_p| > N_p + \varepsilon$, where $M = |T_p|$ is the set cardinality of T_p, $\varepsilon \geq 1$ is an integer.
2) Calculating the standardization orthogonal basis for channels of the group T_p as

Initialization:

$T_0 = \phi$;

$T = \{1, 2, ..., M\}$;

While $|T_0| < N_p$

For $k \in \overline{T_0}$

$$h_{pk}^s = h_{pk}[I_M - \sum_{i\in\{0\}\cup T_0} h_{pi}^{\mathrm{H}}(h_{pi}h_{pi}^{\mathrm{H}})^{-1}h_{pi}]$$

End

$k^* = \arg\max_{k\in T_0}\left\|h_{pk}^s\right\|$;

$T_0 = T_0 \cup k^*$

End

Step two:

After we get the assembly as T_0, the mutual interference among the selected users can be nulled by selecting appropriate weighting vectors according to the principle of ZFB. One way for the beamforming weights vectors $W(T_0)$ to obtain multi-user interference free is to invert the channel matrix of the selected users $H(T_0)$ as

$$W(T_0) = H(T_0)^{\dagger} \quad (3)$$

where $(\cdot)^{\dagger}$ is denoted pseudo-inverse operation as mentioned before. To optimally solve the problem in (1), the optimal power allocation solution P_p is the power loading matrix obtained through water-filling algorithm under total transmitted power constraint. We give a sub-optimal feasible solution for the problem (1). It can be shown later from simulation results that the system can achieve better throughput performance using the proposed user selection.

V. Computational Complexity Analysis

In the first step of CR-SUS, we need K times inner product operations and $2K$ vector 2-norm calculations. Let B_1 be the computation complexity of the first step. In the second step, when we choose the *k*-th cognitive nodes, we need $B_2 = \sum_{k=1}^{N_p}(M+1-k)[k(2N_p^2+N_p+1)]$. Then the whole computation complexity is $B_1 + B_2$, which is $O(N_c^4)$.

VI. Simulation Results

In this section, the simulation results of our proposed algorithm are presented. In order to evaluate the performance of CR-SUS algorithm, the sum-rate performance is considered. In the simulation, we set $\gamma = 1$, $\varsigma_p = 8dB$.

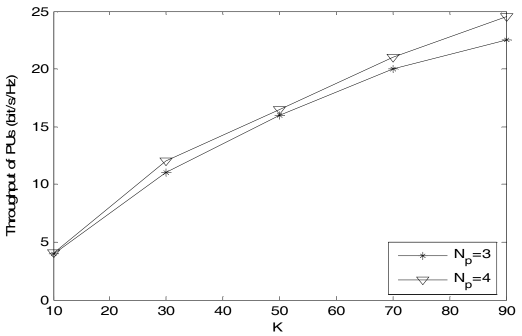

Fig. 3. Sum rates of primary users under K primary users

In Fig 3, the sum rates of primary users under the proposed algorithm, averaged over the channel distributions, as a function of the number of users K. The conclusion from Fig 3 is that the sum rates of primary users becomes larger via the number of primary users can be chosen with K and the number of primary users has been chosen with N_p. For a large number of primary users, the chance to have the best users selected gets higher so the sum-rate increases. And the sum-rate increases because the number of cognitive users exploiting the multi-user diversity.

Fig 4 is plotted as sum rates via DPC power allocation method and using equal power allocation. The figure depicts simulation results using both schemes of power loading are similar in terms of throughput. Though DPC power allocation scheme has much better system performance than the equal power allocation, it is much complex to be employed in a real system.

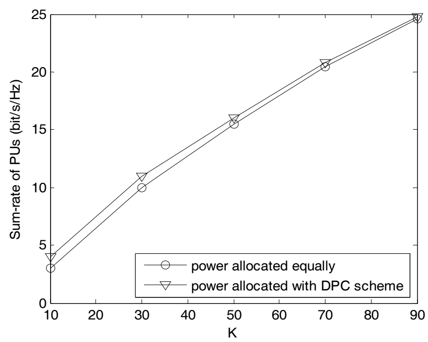

Fig. 4. Sum rates of primary users via different power allocation schemes

VII. Conclusion

In this paper, we mainly discuss one joint detection strategy and one user selection algorithm used in the downlink of CR mesh system simplify the capacity problem by pre-whitening the co-channel interference to primary nodes. In the third section, the cognitive central node control more than one cognitive users to jointly detect the primary channel. In the fourth section, various performance evaluation results demonstrate that the algorithm CR-SUS accommodates for more general case and is able to achieve high sum rate throughput used in CR network. The research also restates that primary nodes should purposefully decrease co-channel interference caused by cognitive nodes and we hope our research should be used to study important performance criteria, and shed lights on the application of cognitive MISO techniques.

References

[1] Wang, Y, "On Cognitive Computing. International Journal of Software Science and Computational Intelligence," Vol.1, no.3, PP.1-15, 2009.
[2] J. Mitola, "Cognitive radio: an integrated agent architecture for software defined radio," Ph.D. dissertation, KTH, Stockholm, Sweden, Dec. 2000.
[3] J. Unnikrishnan, V.V. Veeravalli, "Cooperative sensing for primary detection in cognitive radio," IEEE Journal on Selected Topics in Signal Processing, Vol.2, no.1, PP. 18-27 2008.
[4] Ming guang Xu, Dong lin, "Non-Orthogonal Precoding Matrix Design for MU-MIMO Downlink Channels," in *Proc.* IEEE WCNC 2006, pp. 1311-1315.
[5] Ahmed K, Sadek, K. J. Ray Liu, "Anthony Ephremides. Cognitive Multiple Access Via Cooperation: Protocol Design and Performance Analysis," IEEE Trans.Inf.Theory, Vol 10, pp.3677-3696,2007.
[6] G. Scutari, D. P. Palomar, S. Barbarossa, "Cognitive MIMO Radio," IEEE Trans. Sig. Proc., pp.46-59, 2008.
[7] Karama Hamdi, Wei Zhang, Khaled Ben Letaief, "Joint Beamforming and Scheduling in Cognitive Radio Networks" IEEE GLOBECOM 2007, proceedings.
[8] Buzzi S,Poor H,Saturnino D. Noncooperative wave formadaptation games in multiuser wireless communications[J] . in *Proc.* IEEE Signal Processing Magazine, vol.26, no.5, PP. 64-76, 2009.
[9] S. K Zheng, Y. C Liang, and P. Y Kam, A. T. Hoang "Cross-layered design of spectrum sensingand MAC for opportunistic spectrum access," In *Proc. IEEE WCNC* 2009, PP.1-6, 2009.
[10] H. Weingarten, Y. Steinberg, and S. Shamai, "The capacity region of the Gaussian MIMO broadcast channel," In *Proc. IEEE ISIT* 2004, pp.174-174, 2004.

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