Cross Layer Interference Mitigation Using a Convergent Two-Stage Game for Ad Hoc Networks

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***Abstract*— In this paper, we concentrate on convergence issues of a two stage game namely on joint beamforming and channel allocation in an ad hoc network. Maximization of the received signal-to-interference-plus-noise (SINR) ratios between two communicating nodes under constant transmit power is considered. We propose a convergent sequential distortionless beamforming (SDRB) and cooperative channel allocation (CCA) algorithm which we call as SDRB_CCA, to mitigate the interference in the network. In this algorithm, a suboptimum beamforming algorithm is performed in PHY layer and a cooperative (or non-greedy) channel allocation is assigned based on the definition of potential games in MAC layer in an iterative manner. The payoff of each channel selection includes the interference received at each node as well as the interference that this selection will cause on the other nodes. Simulation results supported our analytical results in the sense that SDRB_CCA converges at the expense of decrease in average rate compared to the optimum joint iterative beamforming and greedy channel allocation (O_JIBGCA) algorithm especially in over-loaded scenarios.**

***Index Terms*— convergence of two-stage games, potential function, cross layer interference mitigation**

I. Introduction

As networks become less integrated and involve more distributed decision making strategies, recent radio technology helps the deployment of smart flexible networks. Thus, nodes can be adjusted to adapt to the changing environment such that the overall network performance is enhanced. Wireless ad hoc networks can be designed to ensure the common requirements for wireless communication systems such as flexibility in the management of available spectrum, higher rates and robustness against interference impairments.

The demand for wireless spectrum use has been growing in the mobile communication industry in the last decades. However, at the same time, the scarce spectrum availability and increased number of users push wireless service providers to search for intelligent ways of spectrum usage against impairments such as interference. Dynamic spectrum access techniques can allow the users to operate in a minimum interference environment by changing the channel accordingly (see [1] for a survey). Channel allocation or spectrum access has been extensively studied especially for cellular networks [2]. For emerging communication technologies other than cellular networks, channel allocation was investigated for wireless local area networks (WLANs) based on weighted graph coloring [3]. For ad hoc networks a fundamental component of efficient radio resource management (or spectrum management) is selecting the *best available channel* [4] [5]. Spectrum access for ad hoc networks can be classified as *cooperative* or *noncooperative* depending on the nodes' decisions. *Noncooperative* channel allocation only consider the performance of each node selfishly [6] [7]. In *cooperative* solutions, each node in the network shares its interference level with all other nodes in the networks. The competitive advantage of cooperative techniques compared to noncooperative ones in terms of each user's system improvement is well established in the literature [8] [9]. On the other hand, overall system performance degradation can occur if the system capacity and energy is concerned because of increased communication overhead during collaboration. However, an effective multiple access control (MAC) protocol can be designed that enables efficient usage of spectrum sharing information [4].

Using multiple-input multiple-output (MIMO) communication systems with beamforming techniques can also minimize the interference seen at receiver antennas. Beamforming algorithms can be properly designed as a means to minimize the total power [10] or to increase the capacity of wireless communication networks [11].

Two-stage games, where parameters in the two layers for each node are adjusted based on the definition of a predefined utility function, have recently been investigated in [12] [5]. In [12], a joint power and channel selection for each node in a noncooperative game is studied. A joint beamforming and greedy channel selection algorithm which improves the data rate of each user in wireless ad hoc networks is given in our previous work [5]. It was shown that using greedy channel allocation with optimal beamforming can yield good results but it is not guaranteed to converge, making it useless from a practical perspective. This non-convergence means that it is not a good candidate for implementation, and motivates further

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theoretical work on a joint channel selection and beamforming game which is guaranteed to converge in finite time.

The field of game theory is still young, as a result analytical convergence results for many large distributed games do not yet exist. The closest proof of convergence for many games is by showing the converge in extensive simulations. It's obvious that any theoretical work on the convergence of distributed games with per node utility functions is an open future research topic.

In this paper, cross layer joint interference mitigation using an efficient spectrum usage according to maximization of a utility function defined for cooperative channel allocation (CCA) in the MAC layer and rate maximization using sequential distortionless beamforming (SDRB) [10] algorithm in the physical (PHY) layer is considered. In proposed algorithm, at the MAC layer, the node pairs iteratively select their best channels cooperatively. Simultaneously at the PHY layer, the nodes with multiple antennas adjust their beamforming patterns such that the overall interference perceived by two communicating node pairs is minimized as well as the data rate is maximized. We call the joint algorithm as SDRB_CCA which is shown to converge using the definition of potential function in MAC layer and suboptimum beamforming in the PHY layer.

II. System Model and Concepts

In our ad hoc network model, pairs of users want to communicate only with each other, i.e. nodes $i \in 1, 2, \cdots, N$, communicate with only one node ($l(i) \neq i$), using symbol stream $b_i(n) \in \mathcal{C}$ with $E|b_i(n)|^2 = 1$. Each node is equipped with M transceiver antennas. Each node has a unit-norm receive/transmit beamformer pair $(\mathbf{w}_i, \mathbf{g}_i)$ with $\mathbf{w}_i, \mathbf{g}_i \in \mathcal{C}^M$ [10].

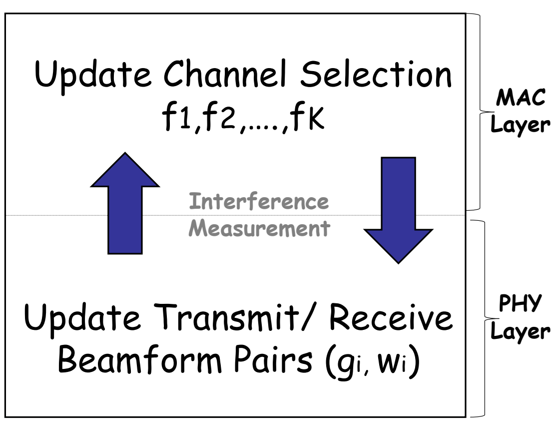

Fig. 1. PHY and MAC layer interactions for the two stage game.

We assume that the available frequency band of the whole network is divided into K orthogonal channels $f_1, f_2, ..., f_K$ of the same bandwidth for node pairs $(i, l(i))$. Each node pair has the capability of switching between these K orthogonal frequencies.

The interactions between the layers of our design algorithm is shown in Fig. 1. PHY layer and MAC layer parameters are related by interference perceived at each node pairs and the mutual parameter modifications at different layers are done by proposed SDRB_CCA algorithm.

The received signal vector $\mathbf{r}_{l(i)}(n) \in \mathcal{C}^M$ corresponding to symbol n at node $l(i)$ is given by

$$\begin{aligned}\mathbf{r}_{l(i)}(n) =& \mathbf{H}_{l(i),i}\mathbf{g}_i P_i b_i(n) + \\ & \sum_{m \neq i, l(i)} \mathbf{H}_{l(i),m}\mathbf{g}_m P_m b_m(n) I(f_m, f_i) + \mathbf{n}_{l(i)}(n),\end{aligned} \tag{1}$$

where $I(f_m, f_i)$ is an interference function which is defined as,

$$I(f_m, f_i) = \begin{cases} 1, & \text{if } f_m = f_i, \text{i.e. node pairs } (m, l(m)) \\ & \text{and } (i, l(i)) \text{ choose the same channel for} \\ & m \neq i \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

and the white Gaussian noise terms $\mathbf{n}_{l(i)}(n) \in \mathcal{C}^M$ have identical covariance matrices $\mathbf{I}$.

The received signal stream $\mathbf{r}_{l(i)}$ is multiplied by unit norm receive beamformer $\mathbf{w}_{l(i)}$. Then,

$$\mathbf{w}_{l(i)}^H \mathbf{r}_{l(i)}(k) = \mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),i}\sqrt{P_i}\mathbf{g}_i b_i(k) + \mathbf{w}_{l(i)}^H \mathbf{y}(k), \tag{3}$$

where

$$\begin{aligned}\mathbf{w}_{l(i)}^H \mathbf{y}(k) = & \sum_{m \neq i, l(i)} \mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),m}\sqrt{P_m}\mathbf{g}_m b_m(k) I(f_m, f_i) \\ & + \mathbf{w}_{l(i)}^H \mathbf{n}_{l(i)}(k).\end{aligned} \tag{4}$$

$M \times M$ the interference-plus-noise covariance matrix at node $l(i)$ is

$$\begin{aligned}\mathbf{R}_{l(i)} &= E\{\mathbf{y}(k)\mathbf{y}(k)^H\} \\ &= \sum_{m \neq i, l(i)} \mathbf{H}_{l(i),m} P_m \mathbf{g}_m \mathbf{g}_m^H \mathbf{H}_{l(i),m}^H I(f_m, f_i) + \mathbf{I}.\end{aligned} \tag{5}$$

The resulting received signal-to-interference plus noise ratio (SINR) at node $l(i)$ due to desired user i becomes

$$\mathbf{\Gamma}_{l(i)} = \frac{P_i |\mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),i}\mathbf{g}_i|^2}{\sum_{m \neq i, l(i)} P_m |\mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),m}\mathbf{g}_m|^2 I(f_m, f_i) + 1}, \tag{6}$$

where $||\mathbf{w}_i||^2 = ||\mathbf{g}_i||^2 = 1$. Denote $\mathbf{P} = [P_1, P_2, \cdots, P_N]^T = \mathbf{C}$ as the transmission powers for the N radios.

The interference-plus-noise value from node $m \neq i, l(i)$ to node $l(i)$ if they are using the same channel is

$$\begin{aligned}\rho_{m,l(i)} &= E\{\mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),m} P_m \mathbf{g}_m b_m(k) b_m(k) \mathbf{g}_m^H \mathbf{H}_{l(i),m}^H \mathbf{w}_{l(i)}\} \\ &+ E\{\mathbf{w}_{l(i)}^H \mathbf{n}_{l(i)}(k)\mathbf{n}_{l(i)}(k)^H \mathbf{w}_{l(i)}\} \\ &= \mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),m} P_m \mathbf{g}_m \mathbf{g}_m^H \mathbf{H}_{l(i),m}^H \mathbf{w}_{l(i)} + 1 \\ &= P_m ||\mathbf{g}_m^H \mathbf{H}_{l(i),m}^H \mathbf{w}_{l(i)}||^2 + 1.\end{aligned} \tag{7}$$

III. SDRB_CCA ALGORITHM

The optimization problem is to maximize $\Gamma_{l(i)}$ subject to a constant transmission power $\mathbf{P}$ for each node i. The transmit beamforming solution for optimal beamforming is [5] [10]

$$\mathbf{g}_i = \arg\max_{\mathbf{g}} \frac{\mathbf{g}^H \mathbf{H}_{l(i),i}^H \mathbf{R}_{l(i)}^{-1} \mathbf{H}_{l(i),i} \mathbf{g}}{\mathbf{g}^H \mathbf{R}_i^* \mathbf{g}}. \quad (8)$$

The iterative algorithm that solves Eq. (8) combined with a greedy channel selection is given in [5] and in this paper, we will call it as optimal joint iterative beamforming and greedy channel allocation (O_JIBGCA) algorithm. However, this algorithm is not guaranteed to be convergent.

In order to guarantee the convergence of beamform patterns in the PHY layer, we apply SDRB algorithm of [10] in which case the idea is to assume $\mathbf{R}_{l(i)} = \mathbf{I}$ (which will result in a suboptimum solution since there will be interference at node $l(i)$) such that the algorithm tries to find the solution to the following equation:

$$\mathbf{g}_i = \arg\max_{\mathbf{g}} \frac{\mathbf{g}^H \mathbf{H}_{l(i),i}^H \mathbf{H}_{l(i),i} \mathbf{g}}{\mathbf{g}^H \mathbf{R}_i^* \mathbf{g}}. \quad (9)$$

Then, the data rate of node i can be computed as

$$\xi_i = log_2(1 + P_i \mathbf{g}_i^H \mathbf{H}_{l(i),i}^H \mathbf{H}_{l(i),i} \mathbf{g}_i). \quad (10)$$

Since update in Eq. (9) depends only on denominator which is only a function of beamform patterns of node i itself, the convergence issues of SDRB algorithm is well established in [10] based on the definition of total interference function. In the following section, we will combine this algorithm with cooperative channel allocation (CCA) which will guarantee the convergence of the two stage game.

Therefore for SDRB_CCA, firstly we will adjust the beamform patterns in the PHY layer and then assign channels at MAC layer.

A. Utility function for channel selection

We are interested in whether the channel allocation strategies will reach to its equilibrium point in MAC layer after the convergence of transmit/receive beamform pairs in the PHY layer i.e. after using SDRB algorithm.

The utility function of the CCA is,

$$\begin{aligned} f_i^* &= \arg\max_{f_i} U_i(f_i) \\ U_i(f_i) &= U_i(f_i, f_{-i}) \\ &= -\sum_{m \neq i, l(i), m=1}^{N} \left(\rho_{m,i} I(f_i, f_m) + \rho_{i,m} I(f_m, f_i)\right), \end{aligned} \quad (11)$$

where $\rho_{m,i}$ defined in Eq. (7). The channel is selected taking into account the interference seen at the receiver node, as well as the interference that this transmitter node causes to other nodes in the network.

Players select actions to maximize their utility functions. We want to determine if there will be a converge point (i.e. a Nash equilibrium (NE)) of the SDRB_CCA game, from which no player would deviate anymore for analyzing the outcome of the game.

B. A Potential Function for channel selection

An exact potential function is defined with the property $U_i(f_i, f_{-i}) - U_i(f_i', f_{-i}) = \mathbb{P}(f_i, f_{-i}) - \mathbb{P}(f_i', f_{-i})$ for all i and f_i, f_i'. A game that has an exact potential function is called an exact potential game and exact potential games converge to a NE while following a best response strategy [13].

We will demonstrate that CCA game with utility functions given by (11) is an exact potential game (EPG) with the following potential function

$$\begin{aligned} \mathbb{P}(f_i, f_{-i}) = \sum_{i=1}^{N} \Bigg(&-\frac{1}{2} \sum_{m \neq i, l(i), m=1}^{N} \rho_{m,i} I(f_i, f_m) \\ &- \frac{1}{2} \sum_{m \neq i, l(i), m=1}^{N} \rho_{i,m} I(f_m, f_i) \Bigg). \end{aligned} \quad (12)$$

Theorem : The cooperative channel allocation game defined by utility function (11) and the potential function (12) is an exact potential game.

Proof: See the Appendix ■

The above theorem shows that SDRB_CCA is guaranteed to converge for channel selections in MAC layer after beamform patterns converge with the suboptimum SDRB algorithm at the PHY layer.

The SDRB_CCA algorithm that minimizes the denominator in Eq. (9) combined with channel selection according to maximization of utility function in Eq. (11) is given in Table I.

TABLE I
SDRB_CCA ALGORITHM

Initialize channels and beamformer pairs for all nodes
For n=1,2,...,ITER
For i=1,2,...,N
Select $f_i^*(n)$ from Eq. (11)
do
Update transmit/receive beamformer pairs at i
$\mathbf{w}'_i(m+1) = \mathbf{R}_i^{-1} \mathbf{H}_{i,l(i)} \mathbf{g}_{l(i)}(m)$
$\mathbf{w}_i(m+1) \leftarrow \mathbf{w}_i'(m+1)/\lvert\lvert \mathbf{w}_i'(m+1) \rvert\rvert$
$\mathbf{g}_i(m+1) \leftarrow \mathbf{w}_i^*(m+1)$
Transmit packet from node i to node $l(i)$
Update transmit/receive beamformer pairs at l(i)
$\mathbf{w}'_{l(i)}(m+1) = \hat{\mathbf{R}}_{l(i)}^{-1} \mathbf{H}_{l(i),i} \mathbf{g}_i(m)$
$\mathbf{g}_{l(i)}(m+1) \leftarrow \mathbf{R}_{l(i)}^* \mathbf{w}_{l(i)}'^*(m+1)$
$\mathbf{g}_{l(i)}(m+1) \leftarrow \mathbf{g}_{l(i)}(m+1)/\lvert\lvert \mathbf{g}_{l(i)}(m+1) \rvert\rvert$
while $\lvert\lvert \mathbf{g}_i(m+1) - \mathbf{g}_i(m) \rvert\rvert > \delta$
$m_i \leftarrow m$
Update beamformers
$\mathbf{g}_{l(i)} \leftarrow \mathbf{g}_{l(i)}(m_i)$, $\mathbf{w}_{l(i)} \leftarrow \mathbf{w}_{l(i)}(m_i)$
$\mathbf{g}_i \leftarrow \mathbf{g}_i(m_i)$, $\mathbf{w}_i \leftarrow \mathbf{w}_i(m_i)$
Obtain ξ_i and $\xi_{l(i)}$
Next i
Next n

IV. SIMULATION RESULTS

In the simulations, every node i can select between $K = 2$ orthogonal frequencies $f_k,\ k = 1, 2, ..., K\ , i = 1, ..., N$. Simulations were carried out with average rate and node frequency selection as outputs for both SDRB_CCA and O_JIBGCA. A rank-5 channel where there are 5 paths with one direct and four multipaths with 6dB below that of the direct path is assumed. The angular spreads of the multipath are uniformly distributed between $[-\pi/2, +\pi/2]$ with respect to direct path, and the pathloss exponent is 2. Fig. 2 shows the node configuration and beamform patterns of the overloaded scenario (i.e. when the number of available orthogonal frequencies is much less to the total number of node pairs in the network) with $N = 20$ nodes with each node having $M = 4$ antenna elements.

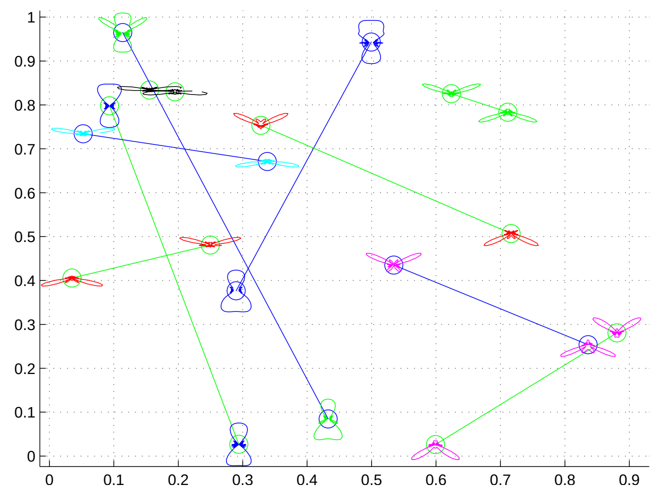

Fig. 2. Considered scenario and node positions with beamform patterns of 20 nodes which are distributed in a 1x1 square meter area.

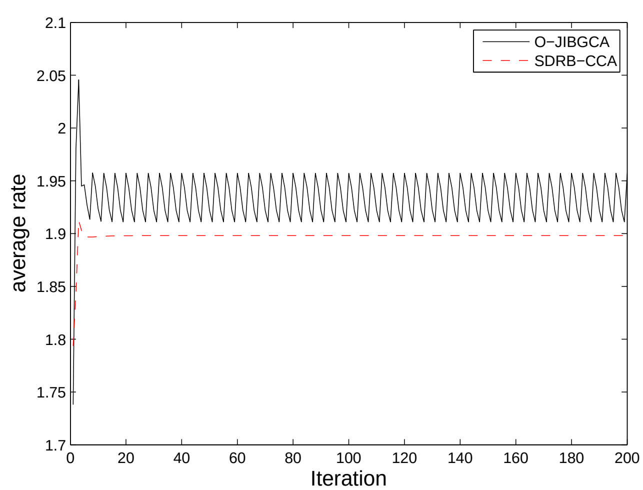

Fig. 3. Average rate comparisons of O_JIBGCA and SDRB_CCA.

Fig 3 illustrates the average rate comparisons of the SDRB_CCA and O_JIBGCA algorithms The O_JIBGCA does not converge and iterates on a loop, whereas the SDRB_CCA converges at the end of iterations. This verifies that our two-stage game reaches to NE points for beamform patterns and channel selections at the expense of decreased average rate.

Fig. 4 illustrates the total number of users selecting one of the each channel versus the iteration number. Two channels are selected from a total number of 20 users. Fig. 4 shows that,

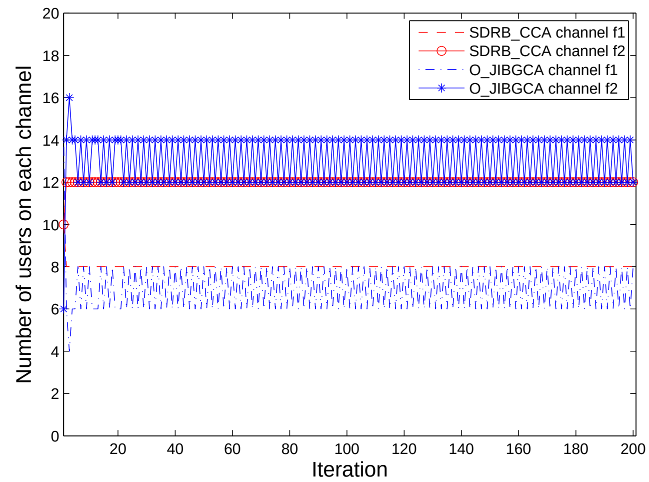

Fig. 4. Total number of users selecting each channel versus iteration for 2 channels and 20 users.

after small amount of shifting between channels, all channel frequencies of nodes converge to a fixed steady state channels for SDRB_CCA whereas, O_JIBGCA does not converge to equilibrium channels. This shows the nonconvergence behavior of O_JIBGCA for channel allocation.

V. Conclusion

In this paper, we examined convergence issues of a two-stage game for users with fixed power requirements through joint channel selection and beamforming which we called as SDRB_CCA in wireless ad hoc networks. Depending on the convergence behavior of suboptimum SDRB algorithm in PHY layer, the cooperative channel selection in MAC layer is guaranteed to converge using the definition of potential games. Simulation results verified the convergence behavior of SDRB_CCA algorithm compared with O_JIBGCA for both beamform patterns and channel selections especially when system is over-loaded.

Appendix

Proof of Theorem

Suppose there exists a potential function of two-stage game:

$$\mathbb{P}(f_i, f_{-i}) = \sum_{i=1}^{N} \left(-\alpha \sum_{m \neq i, l(i), m=1}^{N} \rho_{m,i} I(f_i, f_m) - (1-\alpha) \sum_{m \neq i, l(i), m=1}^{N} \rho_{i,m} I(f_m, f_i) \right), \quad (13)$$

where $0 < \alpha < 1$. Following the same analysis in [4], it can be easily shown that

$$U_i(f_i', f_{-i}) - U_i(f_i, f_{-i}) = \mathbb{P}(f_i', f_{-i}) - \mathbb{P}(f_i, f_{-i}). \quad (14)$$

where

$$U_i(f_i', f_{-i}) - U_i(f_i, f_{-i}) = \mathbb{P}(f_i', f_{-i}) - \mathbb{P}(f_i, f_{-i}) = - \sum_{m \neq i, l(i), m=1}^{N} \rho_{j,i} I(f_i', f_m) - \sum_{m \neq i, l(i), m=1}^{N} \rho_{i,m} I(f_m, f_i') - \left(- \sum_{m \neq i, l(i), m=1}^{N} \rho_{m,i} I(f_i, f_m) - \sum_{m \neq i, m=1}^{N} \rho_{i,m} I(f_m, f_i) \right). \quad (15)$$

Then, the potential function defined in (12) is an EPG of game with $\alpha = \frac{1}{2}$.

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