Joint Iterative Channel Allocation and Beamforming Algorithm for Interference Avoidance in Multiple-Antenna *Ad Hoc* Networks

Engin Zeydan
ezeydan@stevens.edu
Dept. Elect. and Comp. Engineering
Stevens Institute of Technology,
Hoboken NJ 07030

Didem Kivanc-Tureli
dtureli@stevens.edu
Wireless Network Security Center,
Stevens Institute of Technology,
Hoboken NJ 07030

Uf Tureli
utureli@stevens.edu
Dept. Elect. and Comp. Engineering
Stevens Institute of Technology,
Hoboken NJ 07030

***Abstract*— In this paper, we consider the problem of interference suppression by performing a joint iterative beamforming [1] and channel allocation (JIBCA) strategy for wireless nodes under *contracted quality-of-service (QoS)* constraints in an ad hoc network. The objective is to maximize the signal to interference plus noise ratios (SINRs) between two communicating nodes under constant transmit power considering the interference from other nodes in the network. For this purpose, the interference impaired network is modeled as a noncooperative joint beamforming and channel allocation game, in which the payoff includes the maximization of the target SINR and the limiting factor is related to the interference caused by other nodes. The proposed JIBCA algorithm is shown to give better SINR efficiency both with the assumptions of perfect and imperfect channel information availability at the transmit/receive units over the network. It is also shown through simulation results that the JIBCA algorithm converges to Nash equilibriums (NE) and results in SINR efficiency improvement.**

***Index Terms*— multiple antenna ad hoc networks, game theory, interference mitigation**

I. INTRODUCTION

Wireless ad hoc networks can establish connections between communication systems in a flexible way. As networks become less integrated and involve more distributed decision making strategies, recent radio technology helps the deployment of smart flexible networks and nodes. Hence, the network can be adjusted to adapt to the changing environment such that the overall network performance is enhanced. 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.

Channel allocation can be an effective way to increase spectral efficiency [2]. Channel allocation or frequency assignment method has been extensively studied especially for cellular networks [3]. For emerging communication technologies other than cellular networks, channel allocation method is investigated for wireless local area networks (WLANs) based on weighted graph coloring [4]. For cognitive radios, a dynamic channel allocation scheme based on a potential game is presented in [5]. Channel allocation problem for ad hoc networks is expected to attract great attention for future communication system designs.

In spatial beamforming, each communicating node's symbol stream is multiplied by a preselected beamforming weight vector for transmission through multiple antennas such that the overall interference due to other multiple nodes which are using the same frequency simultaneously is minimized. Capacity achieving linear precoders and beamformers are studied for point-to-point MIMO links in [6] and for cellular networks in [7]. For distributed beamforming, spatial beamforming algorithms in ad hoc MIMO networks are proposed in [1] as a noncooperative game for overall power minimization of the network under a QoS constraint.

The use of joint iterative channel allocation (or frequency selection) and spatial beamforming can solve the problem of scarce spectrum availability and can significantly improve the *contracted quality of service (QoS)* of multiple antennas wireless ad hoc networks. In *ad hoc* networks with no centralized controllers, it may not be possible to ensure a guaranteed QoS due to lack of centralized controllers [8]. Therefore, instead of providing guaranteed QoS, it is more reasonable to resort to the concept of contracted QoS. The JIBCA algorithm in this paper attempts to achieve a flexible target SINR desired by the users under constant transmit power. If this target SINR is not achievable due to strength of interference, the algorithm attempts to achieve the next lower QoS by lowering the requested user's target SINR.

At the network level, the node pairs appropriately select their transmission channel frequencies and simultaneously at the physical layer, the nodes with multiple antennas adjust their spatial beamforming patterns such that the overall interference sensed by two communicating node pairs can be minimized jointly while meeting the QoS constraint. In this way, the total network throughput can be maximized or the total transmission power can be minimized while enforcing a

This work was supported in part by by National Science Foundation (NSF) Grant CNS-0520232, CNS-043-5348, Winsec under U.S. Army Contract W15QKN-05-D-0011, AFOSR DURIP grant FA9550-05-1-0329, Sintel under U.S. Office of Naval Research (ONR) Grant N00014-05-1-063 and U.S. Government.

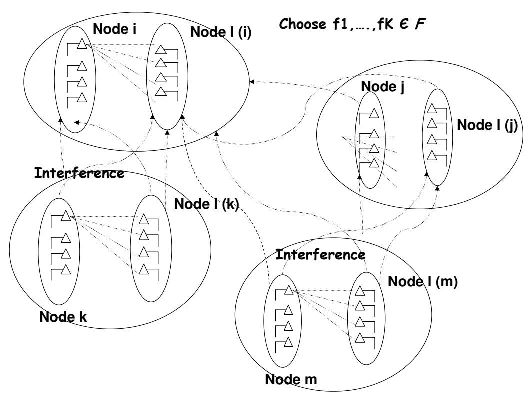

Fig. 1. Node pairs and interference of other nodes on node pairs $(i, l(i))$ due to beamforming and channel allocation.

QoS constraint.

In this paper, we assume that the nodes in the ad hoc network are selfish and want to maximize their own performance without necessarily respecting the system objectives. Therefore, nodes adapt to the changing environment independently such that the overall interference seen between two communicating users in the network is minimized. We investigate a distributed adaptation strategy in order to reduce the interference and consequently facilitate multi-user communication in multiple antenna ad hoc networks. We assume that the node pairs can measure the local interference on different frequencies and can adjust to the changing environment by optimizing their beamforming pattern for a given channel quality (for example, meeting the contracted QoS constraint) and by possibly switching to a different frequency channel.

Game theory can be used as a useful tool for designing and analyzing the behavior of wireless nodes that make independent decisions based on the interactions with other nodes and on the changing environment [9]. We can define the interactions between nodes which have multiple transmit and receive antennas in an ad hoc network within a game theoretic framework. The nodes can optimize their performance by modifying their transmission parameters, such as frequency, bandwidth, power, beamforming patterns etc. This optimization can influence their performance as well as the performance of neighboring players. The selfishness of the participants is a motivation for noncooperation.

II. System Model and Concepts

The ad hoc network considered here consists of multiple transmit and receive antenna node pairs as shown in Fig. 1.

Interference is caused at a receive node by transmissions from the user nodes different from the one associated with that particular receive node at the same channel frequency. 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 $E|b_i(n)|^2 = 1$ similar to [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 $\mathbf{w}_i, \mathbf{g}_i \in \mathcal{C}^M$. An unnormalized beamformer $\hat{\mathbf{g}}_i = \sqrt{P_i}\mathbf{g}_i$ is defined where P_i is the transmitted power of node i [1].

We assume that all nodes have some packets to transfer and all nodes in the network can transmit simultaneously. The network is assumed to be synchronous and the set of available orthogonal channels is denoted by $\mathcal{F}$. We assume that the available frequency band of the whole network is divided into $|\mathcal{F}|$ orthogonal channels $f_{1,i}, f_{2,i}, ..., f_{|\mathcal{F}|,i}$ of the same bandwidth for node pairs $(i, l(i))$. Each node has the capability of switching between K orthogonal frequencies where $K < |\mathcal{F}|$. Since we assume that there is a two way communication link between node pairs $(i, l(i))$, the multiple transmitters and the receivers of each node are able to coordinate and can select the same channels over all antennas to communicate. All antennas that participate in communication between nodes $(i, l(i))$ can select only a single transmission channel and other transmitter and receiver node pairs $(j \neq i, l(j))$ can select different transmission channels than node pairs $(i, l(i))$.

Slow, flat-fading channels are assumed, so that the channel matrices $\mathbf{H}_{i,j}$ are quasi-static. The received signal vector $\mathbf{r}_{l(i)}(n) \in \mathcal{C}^M$ corresponding to symbol n at node $l(i)$ is given by (cf. [1, Eq. (1)])

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

where $I(m, l(i))$ is an interference function which is defined as,

$$I(m, l(i)) = \begin{cases} 1, & \text{if node pairs } (m, l(m)) \text{ and} \\ & (i, l(i)) \text{ choose the same channel } f_{k,i} \in \mathcal{F} \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

and the white Gaussian noise terms $\mathbf{n}_i(n) \in \mathcal{C}^M$ have identical covariance matrices $\mathbf{I}$. The resulting received SINR at node $l(i)$ due to desired user i is (cf. [1, Eq. (2)])

$$\mathbf{\Gamma}_{l(i)} = \frac{P_i |\mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),i} \mathbf{g}_i|^2}{\sum_{m \neq i, l(i)} P_m |\mathbf{w}_{l(i)}^H \mathbf{H}_{l(i),m} \mathbf{g}_m|^2 I(m, l(i)) + 1} \tag{3}$$

where $||\mathbf{w}_i|| = ||\mathbf{g}_i|| = 1$. The *contracted QoS* constraint is $\Gamma_i \geq \gamma_0$ for all i. Denote $\mathbf{P} = [P_1, P_2, \cdots, P_N]^T$ as the transmission powers for the N radios. The goal is to maintain *contracted QoS* under constant transmit power $\mathbf{P} = \mathbf{C}$.

SINR efficiency ζ_i^n is defined as the ratio of the attained SINR (Γ_i^n) to the SNR (γ_i^{su}) at node i for iteration n. In the absence of multiuser interference, the SNR γ_i^{su} attained for single user (*su*) at node i is found as $\gamma_i^{su} = P_i^{su}\lambda_{max}(\mathbf{H}_{l(i),i}^H \mathbf{H}_{l(i),i})$, where $\lambda_{max}(\mathbf{A})$ is the maximum eigenvalue of matrix $\mathbf{A}$ [1] and P_i^{su} is set to a constant value. The SINR efficiency $\zeta_i^n \in [0, 1]$ at iteration n for node i is defined by

$$\zeta_i^n = \frac{\Gamma_i^n}{\gamma_i^{su}} = \frac{\Gamma_i^n}{P_i^{su}\lambda_{max}(\mathbf{H}_{l(i),i}^H \mathbf{H}_{l(i),i})}. \tag{4}$$

III. Spatial Beamforming and Channel Allocation Structure

Antenna diversity combining can be properly designed as a means to minimize the total power [1], [11] or to increase the capacity of wireless communication networks [10]. An antenna beam pattern that adjust the antenna gains to form nulls towards the direction of the interferers while keeping a constant gain towards the directions of the multipath of the intended receiver can be designed using receive antenna arrays. The minimum variance distortionless response (MVDR) beamformer [1] [12] can adjust the array weights properly such that the sum of interference and noise is minimized as shown in Figure 2.

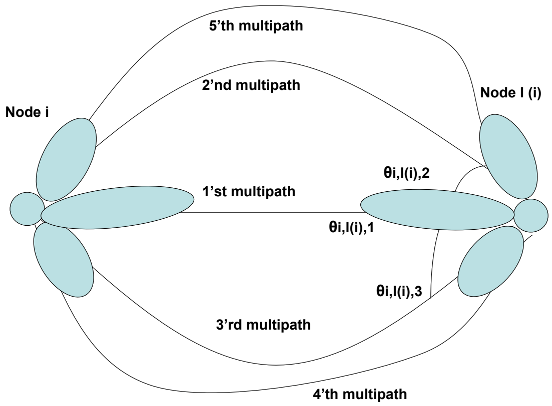

Fig. 2. Multipath propagation environment showing five paths between transmit and receive antennas with $\theta_{i,j,k}$ representing the received angle of the multipath corresponding to transmission from node i to node $l(i)$ with multipath k.

The unnormalized MVDR receive beamformer at node $l(i)$ is defined by [1]

$$\mathbf{w}'_{l(i)} = \mathbf{R}_{l(i)}(\hat{g}_{-i})^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i \tag{5}$$

The interferer plus noise covariance at node $l(i)$ is defined as (cf. [1, Eq. (4)])

$$\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-i}, f_{k,i}) = \sum_{m\neq i,l(i)} \mathbf{H}_{l(i),m}\hat{\mathbf{g}}_m\hat{\mathbf{g}}_m^H\mathbf{H}_{l(i),m}^H I(m,l(i)) + \mathbf{I} \quad \forall i = 1,2,\cdots,N \tag{6}$$

where $f_{k,i} \in \mathcal{F}$, $\hat{\mathbf{g}}_{-i} = (\hat{\mathbf{g}}_l : l \neq i, l(i))$ denotes all beamformers $\hat{\mathbf{g}}_l$ for $l \neq i, l(i)$. Note that the interferer plus noise covariance matrix at node $l(i)$ is defined similar to [1, Eq. (4)] except that we have embedded the channel frequency selection capability to node $l(i)$. We select the frequency for node pairs $(i, l(i))$ such that,

$$f^*_{k,i} = \arg\min_{f_{k,i}\in\mathcal{F}} (||\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-i}, f_{k,i})||_F^2 + ||\mathbf{R}_i(\hat{\mathbf{g}}_{-l(i)}, f_{k,i})||_F^2) \tag{7}$$

where $\|\mathbf{X}\|_F^2$ denotes the Frobenius norm of $\mathbf{X}$. Note that, every node pair $(i, l(i))$ can select their joint channel frequency $f_{k,i}$ and transmit spatial beamforming $\mathbf{g}_i$ such that the overall sum of the norm of the interference vectors at these node pairs is minimized.

IV. IMMSE spatial beamforming with no channel allocation (IB_NCA) and greedy spatial beamforming with no channel allocation (GB_NCA) algorithms

The optimization problem is defined as,

$$\text{Minimize} \quad -\Gamma_{l(i)} \ \text{ subject to } \ \sum_{i=1}^{N} ||\hat{\mathbf{g}}_i||^2 = C' \ \ \forall i \tag{8}$$

where C' is some constant.

The corresponding Lagrangian is obtained by substituting the MVDR beamformer (5) into the SNR (3) and imposing the constraints, yielding (cf. [1, Eq. (6)])

$$L(\mathbf{g}) = -\sum_{i=1}^{N} \hat{\mathbf{g}}_i^H \mathbf{H}_{l(i),i}^H \mathbf{R}_{l(i)}^{-1} \mathbf{H}_{l(i),i}\hat{\mathbf{g}}_i + \sum_{i=1}^{N}\lambda_i\left(||\hat{\mathbf{g}}_i||^2 - C'\right) \tag{9}$$

Theorem : Stationary points of the Lagrangian (9) are given by the following eigenvectors:

$$\mathbf{g}_i = \mathbf{T}_i^{-1}\mathbf{H}_{l(i),i}^H\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-\mathbf{i}})^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i \tag{10}$$

If we multiply both sides of (10) by $\mathbf{g}_i^H\mathbf{T}_i$, we obtain,

$$\mathbf{g}_i = \arg\max_{\mathbf{g}} \frac{\mathbf{g}^H\mathbf{H}_{l(i),i}^H\mathbf{R}_{l(i)}^{-1}(\hat{\mathbf{g}}^{\mathbf{n}}_{-\mathbf{i}})\mathbf{H}_{l(i),i}\mathbf{g}}{\mathbf{g}^H\mathbf{T}_i\mathbf{g}} \tag{11}$$

where the pseudocovariance matrix $\mathbf{T}_i$ is given by

$$\mathbf{T}_i = \left[\sum_{k\neq i,l(i)} \mathbf{H}_{l(k),i}^H P_k \mathbf{w}'_{l(k)}(\mathbf{w}'_{l(k)})^H\mathbf{H}_{l(k),i} + \lambda_i\mathbf{I}\right]^{-1} \tag{12}$$

and $P_k = ||\hat{\mathbf{g}}_\mathbf{k}||^2 = C$. Then, the constrained QoS at node i is satisfied with equality and becomes

$$\gamma_i = P_i\mathbf{g}_i^H\mathbf{H}_{l(i),i}^H\mathbf{R}_{l(i)}^{-1}(\hat{\mathbf{g}}^{\mathbf{n}}_{-\mathbf{i}})\mathbf{H}_{l(i),i}\mathbf{g}_i \tag{13}$$

Proof: See Appendix.

We call the iterative algorithm that solves jointly the equation (11) and (13) as IB_NCA which minimizes a measure of interference to other nodes. It is similar to IMMSE distributed beamforming algorithm of [1] but, the algorithm in [1] tries to minimize the total transmit power under a QoS constraint.

On the other hand, consider the GB_NCA which does not consider the interference that a node will cause to other nodes. The algorithm tries to find joint solution of the following equations,

$$\begin{aligned}\mathbf{g}_i^{n+1} &= \arg\max_{\mathbf{g}_i} \mathbf{g}_i^H\mathbf{H}_{l(i),i}^H\mathbf{R}_{l(i)}^{-1}(\hat{\mathbf{g}}^{\mathbf{n}}_{-\mathbf{i}})\mathbf{H}_{l(i),i}\mathbf{g}_i \\ \gamma_i &= P_i\mathbf{g}_i^H\mathbf{H}_{l(i),i}^H\mathbf{R}_{l(i)}^{-1}(\hat{\mathbf{g}}^{\mathbf{n}}_{-\mathbf{i}})\mathbf{H}_{l(i),i}\mathbf{g}_i\end{aligned} \tag{14}$$

where $P_i = C$ for all i. In other words, for both algorithms IB_NCA and GB_NCA, we consider constant transmission power P_i for all i and contracted QoS such that the attained SINR γ_i, will depend on the the multiuser interference between two communicating node pairs $(i, l(i))$.

Note that in (11), the optimum transmit/receive beamformer is calculated without presenting the channel selection capability to the node pairs. In the following section, we modify the above algorithm and present a new JIBCA algorithm which iteratively selects the channel frequency and transmit/receive spatial beamforming.

V. Joint Iterative Beamforming and Channel Allocation (JIBCA) algorithm

We want to add the channel allocation capability to every node to the above IB_NCA under constant transmit power. For this reason, in (11), instead of $\mathbf{R}_{l(i)}^{-1}(\mathbf{g}_{-i}^{n})$, we substitute $\mathbf{R}_{l(i)}^{-1}(\mathbf{g}_{-i}^{n}, f_{k,i}^{n})$ of (6).

JIBCA combines the channel allocation and beamforming algorithm of IB_NCA. In Table I, we consider the iteration of the algorithm for every n, where the current transmit beamformers are $\mathbf{g}_i(n)$. For every node, the channel frequency $f_{k,i}(n)$ is updated for node pairs $(i, l(i))$. At the same time, every node updates its unit-norm MMSE/MVDR receive beamformer $\mathbf{w}_i(n)$, with all other transmit beamformers $\hat{\mathbf{g}}_{-i}^{n}(n)$ held fixed [1]. Node i then sets its trial transmit beamformer to $\mathbf{g}_i(n) = \mathbf{w}_i^{*}(n)$ for subsequent transmission to $l(i)$. Node $l(i)$ computes its receive beamformer $\mathbf{w}_{l(i)}(n)$ using training sequences from i and sets $\mathbf{g}_{l(i)}(n) = \mathbf{w}_{l(i)}^{*}(n)$.

After the transmit/receive beamformers and channel frequencies are updated, the SINR γ_i^n is calculated using the link SNR estimate $\Gamma_{l(i)}(\hat{\mathbf{g}}_{\mathbf{i}}, \hat{\mathbf{g}}_{-\mathbf{i}}, f_{k,i}) = \hat{\mathbf{g}}_{\mathbf{i}}^{H}\mathbf{H}_{l(i),i}^{H}\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-\mathbf{i}}, f_{k,i})^{-1}\mathbf{H}_{l(i),i}\hat{\mathbf{g}}_{\mathbf{i}}$ at node $l(i)$ under constant transmit power P_i at the end of iteration i.

In our scenario, the pair nodes are the players of the game. The joint channel allocation and beamforming game will constitute the actions for the players in the game. The utility function of the JIBCA algorithm can be given by the following (cf. [1, Eq. (19)]),

$$\begin{aligned} &\mathbf{g}_i^{n+1}, f_{k,i}^{n+1} = \arg\max_{\mathbf{g}_i, f_{k,i}} u_i\left(\mathbf{g}_i, \hat{\mathbf{g}}_{-i}^{n}, f_{k,i}^{n}\right) \\ &u_i\left(\mathbf{g}_i, \hat{\mathbf{g}}_{-i}^{n}, f_{k,i}^{n}\right) = \eta\big(\gamma_i - P_i \mathbf{g}_i^{H}\mathbf{H}_{l(i),i}^{H}\mathbf{R}_{l(i)}^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i\big) \\ &+ ln\ \left(\mathbf{g}_i^{H}\mathbf{H}_{l(i),i}^{H}\mathbf{R}_{l(i)}^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i\right) \\ &- ln\ \left(\mathbf{g}_i^{H}\mathbf{R}_i^{*}(\mathbf{g}_{-i}, f_{k,-i}^{n})\mathbf{g}_i\right) \end{aligned} \tag{15}$$

where $\mathbf{R}_{l(i)}^{-1} = \mathbf{R}_{l(i)}^{-1}(\mathbf{g}_{-i}^{n}, f_{k,i}^{n})$ is defined in Eq. (6) and $\eta(x)$ is any continuous concave function with a global maximum at zero [1].

In [1] and [9], it was shown that greedy interference avoidance using beamforming [1] and waveform adaptation [9] techniques does not always lead to convergence [9] or better social behavior (e.g. lower overall sum power) [1]. In simulation results, we verify the effectiveness of JIBCA algorithm which will yield better SINR improvement over all communicating links in the networks compared to IB_NCA and GB_NCA algorithms with constant powers P_i and with constant total channel bandwidth. Simulations show that joint iterative channel selection and beamforming game converges to steady-state points i.e. Nash Equilibrium (NE).

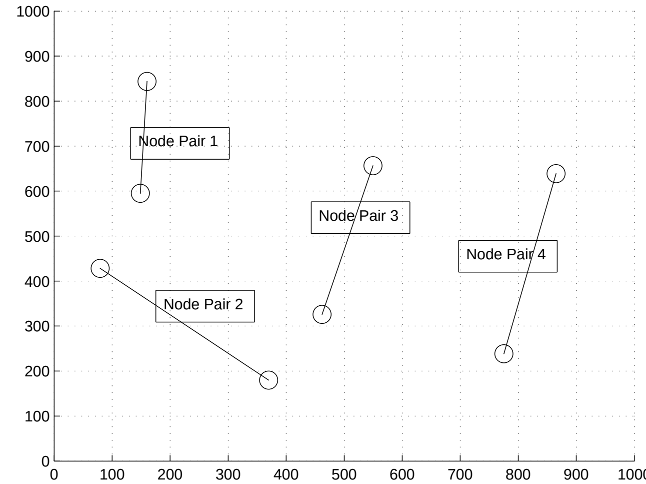

Fig. 3. Considered scenario and node positions which are distributed in a 1000x1000 square meter area.

VI. Simulation Results

In the simulations, we assume without loss of generality (w.l.o.g) every node i can select between K=2 orthogonal frequencies $f_{k,i} \in \mathcal{F},\ k = 1, 2,\ i = 1, ..., N$ (which is available to the entire system in the network) depending on the norm of the interference plus noise covariance of (6) at node $l(i)$. Simulations were carried out with average SINR efficiency (which is the average of the node SINRs defined in (4) over all nodes $i = 1, ..., N$) and node frequency selection as outputs. A rank-3 channel is assumed in which there are 3 paths with one direct and two multipaths with 3 dB below that of the direct path. The angular spreads of the multipath are $\pm\pi/4$ with respect to direct path, and the pathloss exponent is 2 [1]. Fig. 3 shows the node configuration with $N = 8$ nodes and each node has $M = 8$ antenna elements which has a uniform linear array (ULA) model similar to [1]. JIBCA in Table I, GB_NCA and IB_NCA uses the true channels and covariances to compute $\mathbf{g}_i(n)$ and $f_{k,i}(n)$. The channel allocation and beamform patterns are obtained after 200 iterations.

Fig. 4 and Fig. 5 depict the evolution of SINR efficiency for each node in JIBCA and IB_NCA algorithms respectively. After about 15 iterations, the JIBCA and IB_NCA algorithms converges to a NE. All the node pairs of JIBCA has efficiency greater than 0.7,whereas some of the node pairs in IB_NCA has efficiency even below 0.2, which shows that the efficiency of JIBCA for all nodes is always better than the IB_NCA algorithm.

Fig. 6 shows the average SINR efficiency comparisons of JIBCA, Joint iterative beamforming with random channel allocation (JIBRCA), IB_NCA and GB_NCA. JIBRCA algorithm performs joint iterative beamforming with random channel allocation at each iteration, hence the algorithm does not converge to a Nash equilibrium point. As can be seen from the figure, the proposed JIBCA algorithm has an average SINR efficiency of 90 % which outperforms the other three algorithms. The comparisons between the JIBCA and JIBRCA algorithms shows that using an iterative channel allocation

TABLE I

JOINT ITERATIVE BEAMFORMING [1] AND CHANNEL ALLOCATION (JIBCA) ALGORITHM

Initialize $f_{k,i}(1)$ for all node pairs and $(\mathbf{w}_i(1), \mathbf{g}_i(1))$ for all nodes randomly
Set $P_i = C$
For n=1,2,...,ITER
    For i=1,2,...,N
        Select $f^*_{k,2i-1}(n) \in \mathcal{F}$ according to Eq. (7)
        Update normalized MVDR beamformer at i
        $\mathbf{w'}_i(n) = \mathbf{R}_i(\hat{\mathbf{g}}^n_{-\mathbf{i}}, f^*_{k,2i-1}(n))^{-1}\mathbf{H}_{i,l(i)}\mathbf{g}_{l(i)}(n)$
        $\mathbf{w}_i(n) \leftarrow \mathbf{w}'_i(n)/||\mathbf{w}'_i(n)||$
        $\mathbf{g}_i(n) \leftarrow \mathbf{w}^*_i(n)$
        Update node l(i) beamformer.
        $\mathbf{w'}_{l(i)}(n) = \mathbf{R}_{l(i)}(\hat{\mathbf{g}}^n_{-\mathbf{i}}, f^*_{k,2i-1}(n))^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i(n)$
        $\mathbf{w}_{l(i)}(n) \leftarrow \mathbf{w'}_{l(i)}(n)/||\mathbf{w}'_{l(i)}(n)||$
        $\mathbf{g}_{l(i)}(n) \leftarrow \mathbf{w}^*_{l(i)}(n)$
        Obtain $\Gamma_{l(i)}(\hat{\mathbf{g}}_{\mathbf{i}}(n), \hat{\mathbf{g}}_{-\mathbf{i}}(n)) = P_i\mathbf{g}_{\mathbf{i}}(n)^H\mathbf{H}^H_{l(i),i}\mathbf{R}^{-1}_{l(i)}\mathbf{H}_{l(i),i}\mathbf{g}_{\mathbf{i}}(n)$ at node $l(i)$
    Next i
Next n

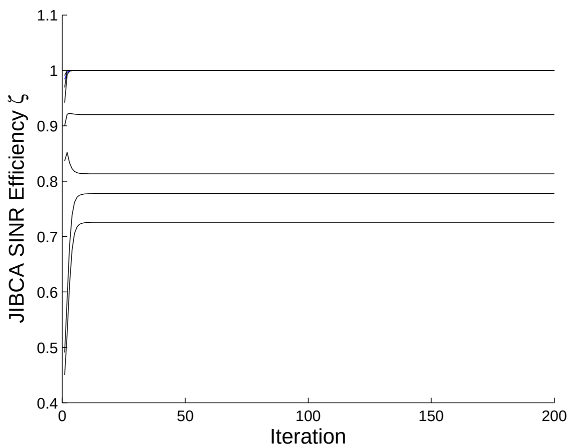

Fig. 4. SINR efficiencies of all the nodes for the JIBCA algorithm in the considered scenario.

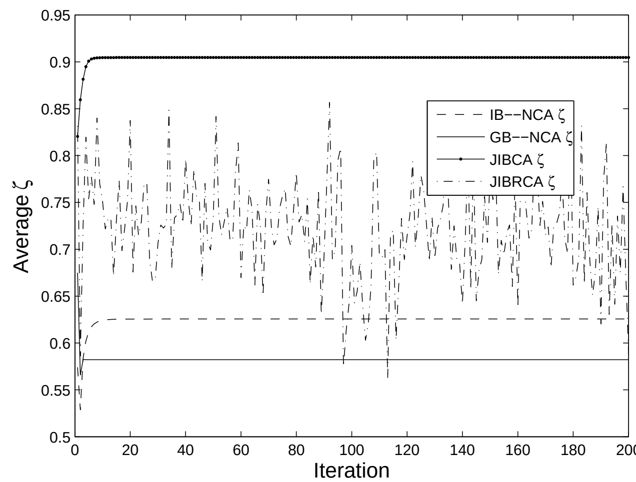

Fig. 6. Average SINR efficiencies of JIBCA, JIBRCA, IB–NCA and GB–NCA algorithms.

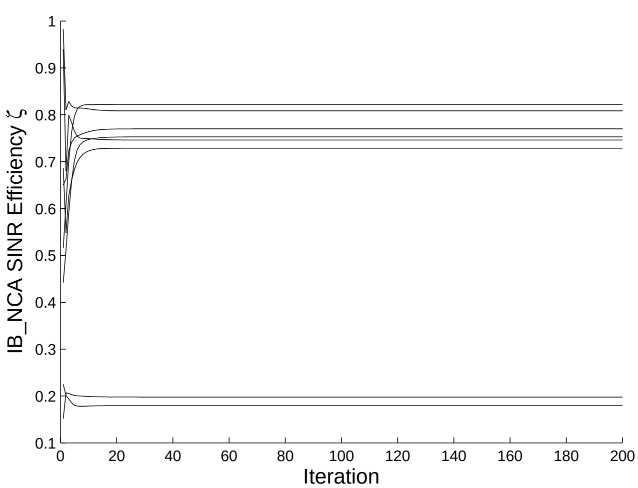

Fig. 5. SINR efficiencies of all the nodes for the IB_NCA algorithm in the considered scenario.

rather than randomly allocating the channels to each node pairs will significantly improve the system performance.

Fig. 7 depicts the evolution of channel allocations (or frequency selections) of all four node pairs in the network for the considered rank-3 channel. Fig. 7 shows that, all node pairs converge to stable frequencies which are the corresponding NE points of all node pairs after small amount of iterations.

In simulations so far, we assumed that the algorithms use the true channels and covariances to compute $\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-i}, f_i)$ since the slow fading, low mobility conditions are assumed. This may not be true in real situations in fast fading environments. In Fig. 8, we replace the true channel matrices by $\mathbf{H}_{i,l(i)} \leftarrow \mathbf{H}_{i,l(i)} + \mathbf{w}_{i,l(i)}$, i.e. each entry of channel matrix is disturbed by AWGN vector $\mathbf{w}_{i,j} \sim CN(0, \sigma^2\mathbf{I})$ where $\sigma^2 = 0.1$ is used in the simulations. Fig. 8 shows that the JIBCA algorithm yields higher total SINR efficiency ζ even in the presence of channel estimation errors between all the transmitting and receiving node pairs $(i, l(i))$. By assigning different frequencies

TABLE II
TOTAL SINR EFFICIENCY COMPARISONS OF JIBCA, IB_NCA AND GB_NCA ALGORITHMS AT THE INITIAL AND FINAL ITERATIONS

	Total SINR efficiency (Iteration 1)	Total SINR efficiency (Iteration 200)
JIBCA	6.5633	7.2368
IB_NCA	4.5931	5.0048
GB_NCA	5.4000	4.6575

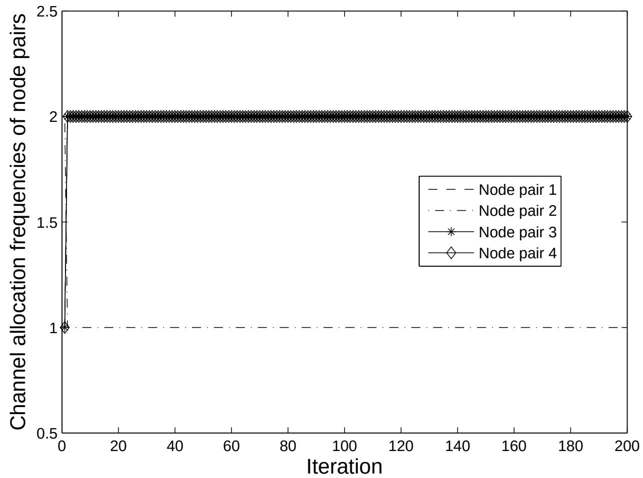

Fig. 7. Channel allocation of all node pairs for JIBCA algorithm. All channel frequencies of nodes converge to a fixed Nash equilibrium point.

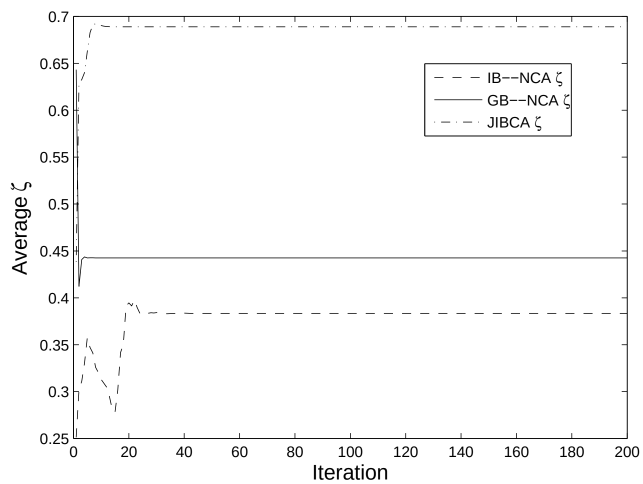

Fig. 8. Average SINR efficiency comparisons of JIBCA, IB_NCA and GB_NCA in the presence of channel estimation and covariance errors.

to node pairs, we reduce the effect of imperfect knowledge of interference covariance vector $\mathbf{R}_{l(i)}(\hat{\mathbf{g}}_{-i}, f_i)$.

Table II shows the attained total SINR efficiency comparisons of the JIBCA algorithm before convergence at iteration 1 and after convergence at iteration 200 with that of the IB_NCA and GB_NCA algorithms at each nodes. This table confirms that JIBCA algorithm has better total SINR efficiency than IB_NCA and GB_NCA algorithms.

VII. CONCLUSION

In this paper, a new iterative joint beamforming and channel allocation (JIBCA) algorithm was considered for ad hoc networks under constant power transmission. It was shown that having joint orthogonal channel selection capability and spatial beamforming in the presence of interference can significantly improve the overall system performance of the communicating nodes. Extensive simulation results showed that JIBCA yielded better average SINR efficiency and improvements compared with IB_NCA and GB_NCA algorithms both in known and partially unknown interference covariance matrix.

Practical implementations of the iterative channel allocation and beamforming adaptation scheme could involve considerable feedback and could increase the overhead in the network. Therefore, as a future work the performance of the system can be investigated for reduced feedback schemes.

APPENDIX
PROOF OF THEOREM

The stationary points $\partial L(\hat{\mathbf{g}})/\partial\hat{\mathbf{g}}_{\mathbf{i}} = \mathbf{0}$ of the Lagrangian (9) are found by direct differentiation with respect to the scalar components $(\mathbf{g}_i)_m$, $m = 1, ..., M$:

$$-2\left(\mathbf{H}_{l(i),i}^H \mathbf{R}_{l(i)}^{-1} \mathbf{H}_{l(i),i} \hat{\mathbf{g}}_i\right)_m + \sum_{k\neq i,l(i)}^{N} \hat{\mathbf{g}}_k^H \mathbf{H}_{l(k),k}^H \mathbf{R}_{l(k)}^{-1} \frac{\partial \mathbf{R}_{l(k)}}{\partial(\hat{\mathbf{g}}_i)_m} \mathbf{R}_{l(k)}^{-1} \mathbf{H}_{l(k),k} \hat{\mathbf{g}}_k + 2\lambda_i (\hat{\mathbf{g}}_i)_m = \mathbf{0} \tag{16}$$

where $\partial\mathbf{R}_{l(k)}^{-1}/\partial(\hat{\mathbf{g}}_{\mathbf{i}})_m = -\mathbf{R}_{l(k)}^{-1}\partial\mathbf{R}_{l(k)}/\partial(\hat{\mathbf{g}}_{\mathbf{i}})_m \mathbf{R}_{l(k)}^{-1}$ is used. Now, substitute

$$\frac{1}{2}\frac{\partial \mathbf{R}_{l(k)}}{\partial(\hat{\mathbf{g}}_{\mathbf{i}})_{\mathbf{m}}} = \mathbf{H}_{l(k),i}\hat{\mathbf{g}}_{\mathbf{i}} \frac{\partial \hat{\mathbf{g}}_{\mathbf{i}}^H \mathbf{H}_{l(k),i}^H}{\partial(\hat{\mathbf{g}}_i)_m} = \mathbf{H}_{l(k),i}\hat{\mathbf{g}}_{\mathbf{i}}\left(\mathbf{H}_{l(k),i}\right)_m \tag{17}$$

into (16), where $\mathbf{R}_{l(k)}$ is defined in Eq. (6) and $(\mathbf{H}_{l(k),i}^H)_m$ is the m'th row of the matrix. Then,

$$\lambda_i \hat{\mathbf{g}}_{\mathbf{i}} - \mathbf{H}_{l(i),i}^H \mathbf{R}_{l(i)}^{-1} \mathbf{H}_{l(i),i} \hat{\mathbf{g}}_{\mathbf{i}} + \sum_{k\neq i,l(i)} \mathbf{H}_{l(k),i} \mathbf{R}_{l(k)}^{-1} \mathbf{H}_{l(k),k} \hat{\mathbf{g}}_{\mathbf{k}} \hat{\mathbf{g}}_{\mathbf{k}}^H \mathbf{H}_{l(k),k}^H \mathbf{R}_{l(k)}^{-1} \mathbf{H}_{l(k),i} \hat{\mathbf{g}}_{\mathbf{i}} = \mathbf{0} \tag{18}$$

Substituting the unnormalized MVDR beamformer definition $\mathbf{w}'_{l(i)} = \mathbf{R}_{l(i)}^{-1}\mathbf{H}_{l(i),i}\mathbf{g}_i$ into (18) yields

$$\mathbf{g}_i = \left[\sum_{k\neq i,l(i)} \mathbf{H}_{l(k),i}^H P_k \mathbf{w}'_{l(k)} (\mathbf{w}'_{l(k)})^H \mathbf{H}_{l(k),i} + \lambda_i \mathbf{I}\right]^{-1} \mathbf{H}_{l(i),i}^H \mathbf{R}_{l(i)}^{-1} \mathbf{H}_{l(i),i} \mathbf{g}_i, \tag{19}$$

which is (10) with $\mathbf{T}_i$ defined in (12).

References

[1] R.A. Iltis, S.J. Kim, D. Hoang, “Noncooperative iterative MMSE beamforming algorithms for ad hoc networks”, *IEEE Transactions on Communications*, vol. 54, no. 4, pp: 748-759, April 2006.

[2] M. Felegyhazi, M. Cagalj, S. Saeedi Bidokhti and J.-P. Hubaux, “Non-cooperative Multi-radio Channel Allocation in Wireless Networks”, *in Proceedings of Infocom'07*, May 6-12, 2007, Anchorage, USA

[3] I. Katzela and M. Naghshineh, “Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey”, *IEEE Personal Communications*, 3(3), pp.10-31, Jun. 1996.

[4] A. Mishra, S. Banerjee, and W. Arbaugh, “Weighted coloring based channel assignment for WLANs”, *Mobile Computing and Communications Review (MC2R)*, 9(3), pp. 19–31, 2005.

[5] N. Nie, C. Comaniciu, “Adaptive channel allocation spectrum etiquette for cognitive radio networks,” *in Proc. IEEE DySPAN 2005*, pp. 269-278, November 2005.

[6] H. Sampath, P. Stoica, and A. Paulraj, “Generalized linear precoder and decoder design for MIMO channels using the weighted MMSE criterion,” *IEEE Trans. Commun.*, vol. 49, no. 12, pp. 2198-2206, Dec. 2001.

[7] F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, “Transmit beamforming and power control for cellular wireless systems,” *IEEE J. Sel. Areas Commun.*, vol. 16, no. 10, pp. 1437-1450, Oct. 1998.

[8] E. Baccarelli, M. Biagi, and C. Pelizzoni, “A Distributed Power-Allocation and Signal-Shaping Game for Multiple-Antenna ad-hoc networks impaired by Multiple-Access Interference ”, *IEEE Transactions on Vehicular Tech.*, vol. 55, no. 6, pp. 1862-1876, Nov. 2006

[9] R. Menon, A. B. MacKenzie, R. M. Buehrer, J. H. Reed, “A Game-Theoretic Framework for Interference Avoidance in Ad hoc Networks”, *GLOBECOM '06* Nov. 2006.

[10] S. Ye and R. S. Blum, “Optimized signaling for MIMO interference systems with feedback,” *IEEE Trans. Signal Process.*, vol. 51, no. 11, pp. 2839-2848, Nov. 2003.

[11] M. C. Bromberg and B. G. Agee, “Optimization of spatially adaptive reciprocal multipoint communication networks,” *IEEE Trans. Commun.*, vol. 51, no. 8, pp. 1254-1257, Aug. 2003.

[12] J. Chang, L. Tassiulas, and F. Rashid-Farrokhi, “Joint transmitter receiver diversity for efficient space division multiaccess,” *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, pp. 16-27, Jan. 2002.