Iterative Beamforming and Power Control for MIMO *Ad Hoc* Networks

Engin Zeydan
ezeydan@mix.wvu.edu
Lane Dept. of CSEE,
West Virginia University,
Morgantown, WV, 26506

Didem Kivanc-Tureli
didemk@ieee.org
Dept. of ECE,
WVU Institute of Technology,
Montgomery, WV, 25136

Uf Tureli
tureli@ieee.org
Dept. of ECE,
WVU Institute of Technology,
Montgomery, WV, 25136

***Abstract*— We present a distributed joint power control and transmit beamforming selection scheme for multiple antenna wireless ad hoc networks. Under the total network power minimization criterion, a joint iterative beamforming and power control algorithm is proposed to reduce mutual interference at each node. Total network transmit power is minimized while ensuring a constant received signal-to-interference and noise (SINR) at each receiver. First, transmit beamformers are selected from a predefined codebook to minimize the total power in a cooperative fashion. We also study the interference impaired network as a noncooperative beamforming game. By selecting transmit beamformers judiciously and performing power control, convergence of noncooperative beamformer games are guaranteed throughout the iterations. The noncooperative distributed algorithm is compared with centralized and cooperative solutions through simulation results.**

***Index Terms*— MIMO, ad hoc networks, limited feedback beamforming, game theory**

I. Introduction

Using multiple-input multiple-output (MIMO) techniques in communication has attracted an increasing interest. The use of multiple antennas improves the capacity and the spectral efficiency of communication systems [1] [2]. In general, MIMO techniques in communication systems are addressed in three different systems: point-to-point, cellular, and ad hoc networks. Point-to-point MIMO links are extensively studied in the literature and the great potential of MIMO in point-to-point communication is shown in [1] [3]. In cellular networks, beamforming algorithms are designed as a means to minimize the total power [4] or to increase the capacity using MIMO techniques [5]. In ad hoc networks, without a central controller, beamforming techniques are used to overcome lower system throughput and higher energy consumption. Distributed spatial beamforming algorithms are proposed for ad hoc MIMO networks in [6] where the problem is formulated as a noncooperative game for overall power minimization of the network under a quality-of-service (QoS) constraint.

Linear precoders (eigencoders) and beamformers are well studied for point-to-point MIMO links [7] [8]. In order to lower communication overhead between transmitter and receiver, quantized transmit beamforming codebook design using limited feedback beamforming scheme for single user MIMO systems is studied in [3]. The concept is based on selecting a codeword in a predetermined codebook that is known to both transmitter and receiver. The transmit beamformer is selected from a predefined codebook to reduce latency in highly mobile and unstable communication networks. Moreover, when the communication system needs low rate or has bandwidth constraints, feedback overhead in situations like non-reciprocal channels are substantially reduced using the proposed codebook design approach.

In this paper, we are interested in the power minimization problem in ad-hoc networks using distributed algorithms with limited feedback transmit beamformer selection under a QoS constraint which is constant signal-to-interference and noise ratio (SINR) for all receivers. The global solution to this problem is challenging in ad-hoc networks. Optimal power minimization algorithms are difficult to design for beamforming games, due to the lack of a natural ordering of the actions. For example, the transmit beamformer and power of one node pair affects the SINR of other node pairs, and vice versa. Moreover, if the node pairs belong to different regulation entities, the non-cooperative node pairs may only want to minimize their own transmit power rather than the overall transmit power. Therefore, finding the optimal distributed transmit beamformer solution for the power minimization problem is not straightforward. Our contributions in this paper are twofold: first we study an efficient cooperative beamforming algorithm for power minimization problem, and second we design a noncooperative power minimization scheme using beamforming techniques. We compare the performance of proposed algorithms with the optimal global solution which is found by searching all feasible strategy space.

The rest of this paper is organized as follows. Section II outlines the system model in the paper. The optimization problem and game theoretical interpretation is studied in Section III. The cooperative wireless ad hoc network and non-cooperative counterpart are investigated Section IV. The performance evaluation is provided in Section V. Finally, Section VI concludes this paper.

II. System Model and Concepts

In this paper, we consider a wireless ad hoc network shown in Fig. 1. The ad hoc network consists of multiple transmit and receive antenna node pairs. All nodes are assumed to be

This work was supported in part by National Science Foundation (NSF) Grant CNS-0520232.

using the same channel. The interference comes from the other node pairs which operate simultaneously on the same channels. In this ad hoc network model, there are N node pairs and each node pair $m \in \{1, 2, ..., N\}$ has one transmitter and one receiver. Each node is equipped with T antennas. The complex symbol stream transmitted is $b_m \in \mathbb{C}$ with $E\{|b_m|^2\} = 1$. Each node has a unit-norm receive/transmit beamformer pair $(\mathbf{w}_m, \mathbf{t}_m)$ with $\mathbf{w}_m, \mathbf{t}_m \in \mathbb{C}^T$.

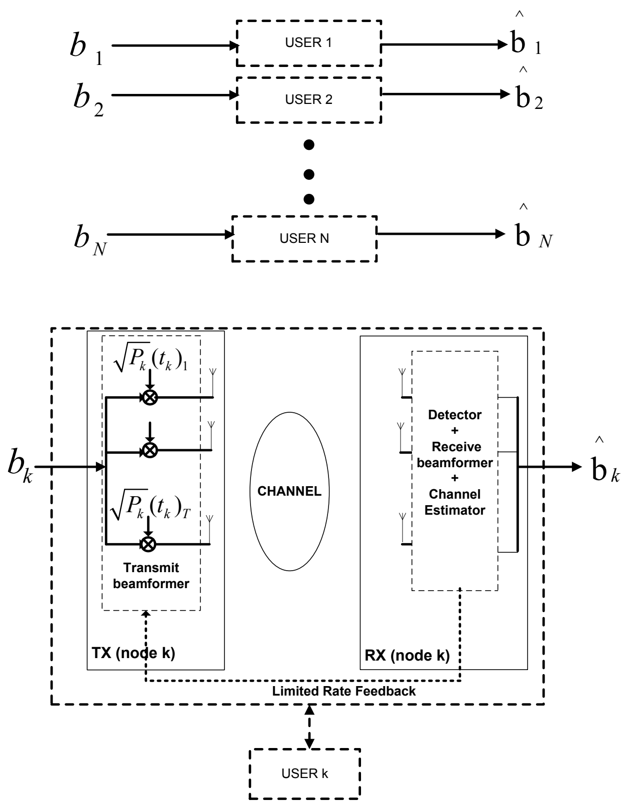

Fig. 1. Multi-user power control and limited feedback transmit beamforming scheme for MIMO ad-hoc networks. $(\mathbf{t}_k)_m$ represents the m'th row of the k'th user's transmitter vector $\mathbf{t}_k$.

The received signal vector $\mathbf{r}_m \in \mathbb{C}^T$ at the $m-$th receiving node is given by

$$\mathbf{r}_m = \sqrt{P_m}\mathbf{H}_{m,m}\mathbf{t}_m b_m + \sum_{i \neq m} \sqrt{P_i}\mathbf{H}_{m,i}\mathbf{t}_i b_i + \mathbf{n}_m, \quad (1)$$

where $\mathbf{H}_{m,i}$ denotes $T \times T$ MIMO channel between the i'th transmitting node and the $m-$th receiving node and is quasi-static P_m is the power of the $m-$th transmitting node. The additive white Gaussian noise terms $\mathbf{n}_m \in \mathbb{C}^T$ have identical covariance matrices $\sigma^2\mathbf{I}_T$ where σ^2 is the noise power and $\mathbf{I}_T$ is the $T \times T$ identity matrix. Note that the first term of the right-hand side of (1) is the desired signal, whereas the second term is the interference from the other transmitting nodes.

The set of available codebook beamformers for the $m-$th transmitting and receiving node pair is denoted by $\Delta_m = \{\mathbf{t}_m^1, \mathbf{t}_m^2, ..., \mathbf{t}_m^\Upsilon\}$ with cardinality Υ. In a limited feedback beamforming system, the receiving node selects a transmit beamformer among the codebook and feeds back the index of the selected beamformer. Each node can select from Υ transmit beamformer vectors. We assume that there is only one way communication between all node pairs. Let $\mathbf{t}_m \in \Delta_m$ be the selected transmit beamformer for the $m-$th transmitting and receiving node pair. Denote $\Theta = [\mathbf{t}_1, \mathbf{t}_2, ..., \mathbf{t}_N]$ and $\mathbf{P} = [P_1, P_2, ..., P_N]$ as the transmit beamformer selection and transmission power vectors for N nodes respectively. The $T \times T$ interference plus noise covariance matrix at the $m-$th receiving node is

$$\mathbf{R}_m(\Theta_{-m}, \mathbf{P}_{-m}) = \sum_{i \neq m} P_i \mathbf{H}_{m,i}\mathbf{t}_i\mathbf{t}_i^H\mathbf{H}_{m,i}^H + \sigma^2\mathbf{I}, \quad (2)$$

where Θ_{-m} and $\mathbf{P}_{-m}$ are the transmit beamfomers and powers of nodes other than m.

The normalized receive beamformer at the $m-$th receiving node is

$$\mathbf{w}_m = \frac{\hat{\mathbf{w}}_m}{||\hat{\mathbf{w}}_m||}, \quad (3)$$

where $\hat{\mathbf{w}}_m = \mathbf{R}_m^{-1}\mathbf{H}_{m,m}\mathbf{t}_m$. The resulting received SINR at the $m-$th receiving node due to the desired transmitter of $m-$th node pair is

$$\mathbf{\Gamma}_m = \frac{P_m|\mathbf{w}_m^H\mathbf{H}_{m,m}\mathbf{t}_m|^2}{\sum_{i \neq m} P_i|\mathbf{w}_m^H\mathbf{H}_{m,i}\mathbf{t}_i|^2 + \sigma^2}, \quad (4)$$

where $||\mathbf{w}_m||^2 = ||\mathbf{t}_m||^2 = 1$ for all m.

The proposed distributed algorithms attempt to achieve a target SINR by adjusting transmit powers. To construct a distributed iterative limited feedback beamforming scheme, let us first consider the case when there is only one node pair in the wireless network. The receiver selects the transmit beamformer from the codebook Δ_1 as

$$\mathbf{t}_1^* = \arg \max_{\mathbf{t}_1 \in \Delta_1} \Gamma_1, \quad (5)$$

where $\mathbf{t}_1^*$ is the optimal transmit beamformer selection for one node pair. Then, the receiver returns the index of the beamformer for transmit beamformer selection $\mathbf{t}_1^*$ and the received SINR, $(\mathbf{t}_1^*)^H\mathbf{H}_{1,1}^H\mathbf{R}_1^{-1}\mathbf{H}_{1,1}\mathbf{t}_1^*$, through a low-rate feedback channel. The transmitter selects the transmitter beamformer in order to minimize its own transmission *power* P_1, where P_1 is updated as

$$P_1 = \frac{\gamma_0}{(\mathbf{t}_1^*)^H\mathbf{H}_{1,1}^H\mathbf{R}_1^{-1}\mathbf{H}_{1,1}\mathbf{t}_1^*}, \quad (6)$$

where γ_0 is the target SINR value.

Consider now the case where N node pairs coexist in the wireless network. Note that for each node pair m, the value of the received SINR, i.e. Γ_m is a function of $(\Theta, \mathbf{P})$. Therefore, the transmit power of one node pair depends not only on its own the transmit beamformer selection, but also the transmit power and transmit beamformer selections of other nodes in the network. Furthermore, in beamforming, if user $i \neq m$ changes its transmit beamformer $\mathbf{t}_i$ to increase its own SINR Γ_i, it can either increase or *decrease* Γ_m, the SINR of link m, depending on the relative positions of the nodes. Therefore, designing an optimal distributed algorithm which converges to a set of beamformers to minimize the overall transmit power while meeting target SINRs for all node pairs is not a straightforward task.

III. Optimization Problem and Game Theoretical Interpretation

The goal is to minimize the transmit power of all nodes $m \in \{1, 2, ..., N\}$ under constant target SINR γ_0. The optimization problem can be defined as,

$$\min_{||\mathbf{w}_m||=||\mathbf{t}_m||=1,\ P_{min}<P_m\leq P_{max}} \sum_{m=1}^{N} P_m \quad (7)$$
$$\text{subject to } \ \Gamma_m \geq \gamma_0, \ \ m \in \{1, 2, ..., N\},$$

where P_{min} and P_{max} are the minimum and maximum transmit powers, respectively. We consider the above problem as a normal form game, which can be mathematically defined by the triplet $\prod = \langle \mathcal{N}, \mathcal{C}, \{U_m\}_{m=1}^{N} \rangle$ where $\prod$ is a game, $\mathcal{N} = \{1, 2, ..., N\}$ is the finite set of players of the game, $\mathcal{C} = C_1 \times C_2 \times, ..., C_N$ represents the set of all available actions for all the players and $\{U_m\}_{m=1}^{N} : \mathcal{C} \rightarrow \mathbb{R}$ is the set of utility functions that the players associate with their strategies. Actions $c_m \in C_m$ for a player m are the transmit powers $P_m \in [P_{min}, P_{max}]$ and the transmit beamformer selections $\mathbf{t}_m \in \Delta_m$.

Players select actions to maximize their utility functions. One of the questions that arise is whether the beamforming selections $\Theta = [\mathbf{t}_1, \mathbf{t}_2, ..., \mathbf{t}_N]$ and eventually power allocations $\mathbf{P} = [P_1, P_2, ..., P_N]$ will converge to a Nash equilibrium (NE) solution. In the following section, we will discuss scenarios where the node pairs are cooperative and non-cooperative in order to search for the best performance and convergence results.

IV. Cooperative and Noncooperative Power Minimization Algorithms using beamforming

A. *Optimal (Centralized) Solution*

In a wireless ad hoc network, the centralized agent can select the transmit beamformers and the corresponding transmit powers to minimize the total transmit power of all transmitting antennas as,

$$(\Theta^*, \mathbf{P}^*) = \arg\min_{\Theta, \mathbf{P}} \sum_{m=1}^{N} P_m(\Theta, \mathbf{P}_{-m}), \quad (8)$$

where $\Theta^* = (\mathbf{t}_1^*, \mathbf{t}_2^*, ..., \mathbf{t}_N^*)$ and $\mathbf{P}^* = [P_1^*, P_2^*, ..., P_N^*]$ are the optimal transmit beamformer and power solutions respectively. The transmit power P_m of $m-$th node pair is defined as

$$P_m(\Theta, \mathbf{P}_{-m}) = \frac{\gamma_0}{\mathbf{t}_m^H \mathbf{H}_{m,m}^H \mathbf{R}_m^{-1} \mathbf{H}_{m,m} \mathbf{t}_m}. \quad (9)$$

where $\mathbf{R}_m$ is a function of $(\Theta_{-m}, \mathbf{P}_{-m})$ as shown in (2). In order to compute (8), the centralized agent evaluates the total network power for Υ^N possible transmit beamforming vector combinations. Finding the centralized transmit beamformer is cumbersome in large-scale wireless ad-hoc network. Next, we will introduce a decentralized power minimization algorithm using cooperative and noncooperative techniques.

B. *Cooperative Power Minimization using Beamforming*

In this section, we consider the scenarios where all node pairs in wireless network are cooperative. In a cooperative game, nodes in the network are able to coordinate and select the transmit beamformer accordingly. From the system point of view, we want to find beamformer assignments such that the overall power in the whole network is minimized. We analyze a cooperative power minimization algorithm (COPMA) which can converge to the optimal Nash equilibrium (NE) with arbitrarily high probability. This method is analogous to the decentralized negotiation method called *adaptive play* [9].

In COPMA, each node pair in the network maintains two variables $P_{current}$ and $P_{updated}$ which are the total transmit power in the network previously and after the random change of transmit beamformer respectively. The key characteristic of COPMA is the randomness deliberately introduced into the decision making process to avoid reaching a local solution. In COPMA, the choices of players (in our case transmit beamformer selections) lead the system to the optimal NE solution with arbitrarily high probability [9]. The summary of COPMA is provided as follows.

Initialization: For each transmitting and receiving pair m, the transmit beamformer is selected randomly and $P_m = P_{max}$ is set $\forall m \in \mathcal{N}$.

Repeat: Randomly choose a node pair m with probability $1/N$. Denote $\mathbf{t}_m(n) \in \Delta_m$ as the current transmit beamformer of $m-$th node pair in iteration n.

1) Set $\mathbf{t}_m(n) = \mathbf{t}_m(n-1)$, $\forall m \in \mathcal{N}$. Calculate P_m as in (9) $\forall m \in \mathcal{N}$ and record the current total network power in $P_{current} = \sum_{m=1}^{N} P_m$.
2) To update node pair m, randomly choose a transmit beamformer, $\mathbf{t}_m^{updated} \in \Delta_m$. Then, compute the updated total network power $P_{updated} = \sum_{m=1}^{N} P_m$ with $\mathbf{t}_m^{updated}$ based on the received power values from all other node pairs $i \in \mathcal{N} \backslash m$.
3) For a *smoothing factor* $\tau > 0$, $\mathbf{t}_m(n) = \mathbf{t}_m^{updated}$ for the $m-$th node pair with probability

$$\frac{1}{1 + \exp\left((P_{updated} - P_{current})/\tau\right)} \quad (10)$$

Until : Predefined number of iteration steps κ.

Note that step-3 of the updating rule implies that if $\mathbf{t}_m^{updated}$ yields a better performance, i.e. $(P_{updated} - P_{current}) < 0$, the $m-$th node pair will change to updated beamformer $\mathbf{t}_m^{updated}$ with high probability. Otherwise, it will keep the current transmit beamformer with high probability. Note also that the tradeoff between COPMA's performance and convergence speed is controlled by the parameter τ. Large τ represents extensive space search with slow convergence, whereas small τ represents restrained space search with fast convergence. The smoothing factor τ is selected to be a function of n such that as n increases, $\tau \downarrow 0$. For example, we choose τ inversely proportional to n^2 in our simulations.

C. *Noncooperative Power Minimization using Beamforming*

In this section, we want to obtain a distributed noncooperative transmit beamforming scheme in MIMO ad-hoc networks which is guaranteed to converge. The interaction among N selfish node pairs is defined as *Non-cooperative Power Minimization Game* (NPMG) where each node pair is attempting to find their own transmit beamformers. In the noncooperative joint iterative limited feedback beamforming and power control game, the N node pairs care about their own utility maximization exclusively, rather than the overall aggregated power.

For NPMG, we use the following utility function for each user for the transmit beamformer and power selection at iteration n:

$$(\mathbf{t}_m(n+1), P_m(n+1)) = \arg\max_{\mathbf{t}_m, P_m} U_m\left(P_m, \mathbf{t}_m, \mathbf{t}_{-m}(n)\right),$$
$$U_m\left(P_m, \mathbf{t}_m, \mathbf{t}_{-m}(n)\right) = \log(P_m \mathbf{t}_m^H \mathbf{H}_{m,m}^H \mathbf{R}_m^{-1} \mathbf{H}_{m,m} \mathbf{t}_m) - \frac{P_m \mathbf{t}_m^H \mathbf{H}_{m,m}^H \mathbf{R}_m^{-1} \mathbf{H}_{m,m} \mathbf{t}_m}{\gamma_0}. \quad (11)$$

The first term in the above utility function represents the SINR maximizing term and the second term represents a pricing function for power minimization.

The procedure for NPMG can be summarized as following:

Initialization : The initial transmit beamformer of each node is selected by maximizing the utility function in (11) when $P_m = P_{max}, \ \forall m \in \mathcal{N}$. Fix the transmit beamformer selections until the end of iterations to prevent unstable transmit beamformer selection oscillations.

Repeat : In each iteration $n = 2, ...\kappa$.

1) For each of the node pairs $m \in \mathcal{N}$, the $m-$th node pair's transmit power is

$$P_m(n+1) = \arg\max_{P_m} U_m\left(P_m, \mathbf{t}_m, \mathbf{t}_{-m}\right). \quad (12)$$

Until : Predefined number of iteration steps κ.

The iterative convergence of NPMG is shown in the next theorem.

Theorem 1 : Starting from a feasible initial network configuration, NPMG converges to a locally minimum transmitted power solution.

Proof: Under fixed transmit beamformers Θ, maximization of the utility function defined in (11) with respect to power is simply a power control algorithm. To find this, we evaluate:

$$\frac{\partial U_m}{\partial P_m} = \frac{1}{P_m} - \frac{\mathbf{t}_m^H \mathbf{H}_{m,m}^H \mathbf{R}_m^{-1} \mathbf{H}_{m,m} \mathbf{t}_m}{\gamma_0} = 0, \quad (13)$$

and the maximizing transmit power P_m is given by

$$P_m = \frac{\gamma_0}{\mathbf{t}_m^H \mathbf{H}_{m,m}^H \mathbf{R}_m^{-1} \mathbf{H}_{m,m} \mathbf{t}_m}. \quad (14)$$

Note that $\partial^2 U_m / \partial^2 P_m = -1/P_m^2 < 0, \forall m \in \mathcal{N}$. Therefore, U_m is a strictly concave function of transmit power P_m under constant transmit beamformers Θ. Therefore, U_m is a quasiconcave function optimized on a convex set $[P_{min}, P_{max}]$. The existence of pure strategy NE point follows directly from the results of game theory [10]. Power control guarantees the convergence of the algorithm to the NE while minimizing the total transmit power iteratively [11]. ■

The above proposed algorithm results in power minimization across the network, while guaranteeing the convergence in a noncooperative manner. We present a detailed performance evaluation of COPMA and NPMG in next section.

V. Simulation Results

In this section, we investigate the performance results of centralized optimization, COPMA and NPMG. We assume that there are $N = 4$ and $N = 8$ transmitting and receiving pairs in two different wireless ad-hoc networks. All transmitting and receiving nodes are randomly located in a square of $100m \times 100m$ area. The distance between each transmitter and receiver is a random distance uniformly distributed between $10m$ and $20m$. Each entry in the channel matrix $\mathbf{H}_{m,i} \ \forall m, i \in \mathcal{N}$ has independent identically distributed entries distributed according to $\mathcal{CN}(0, 1)$. The common target SINR is $\gamma_0 = 15$ dB for all the node pairs. We assume that channels don't vary during the iterations and the Grassmannian codebook of [3] is used. The codebook size is selected to be $\Upsilon = 16$ with $T = 3$ antennas for all the node pairs. We choose $\tau = 0.01/n^2$ for both $N = 4$ and $N = 8$, where n denotes the iteration number. The noise power is $\sigma^2 = 3.16 \times 10^{-13}$ W (-95 dBm) which corresponds to approximate thermal noise power for a bandwidth of 20 MHz. $P_{max} = 100$ mW and $P_{min} = 0$ (no transmission) in our simulations. The maximum number of iterations is $\kappa = 100$. The global optimum solution is obtained only for $N = 4$ by enumerating all feasible strategies, i.e. 16^4 profiles, as the performance benchmark. The results are averaged over 100 different configurations.

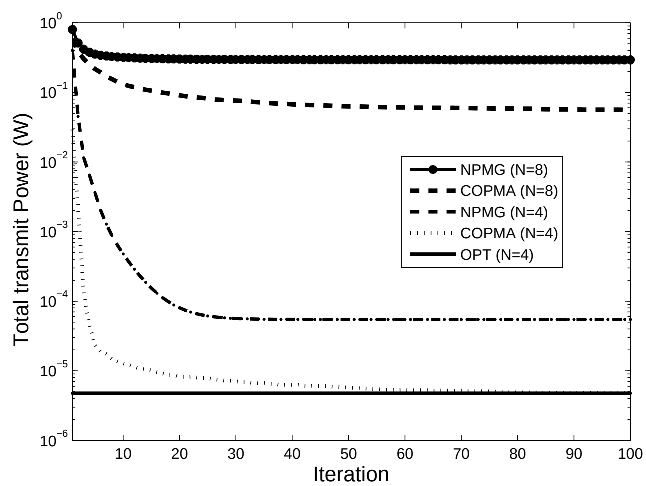

Fig. 2. Total transmit power versus iteration with $T = 3$ and $\Upsilon = 16$.

The performances of total power is shown in Fig. 2. As indicated by the "OPT" curve, the global optimum of minimum power obtained by enumeration approach functions as the lower bound of the overall power for $N = 4$. We observe that COPMA's performance increases with iterations and settles at the global optimum combination at the end of iterations. The non-cooperative players yield inferior performance compared to COPMA in terms of overall power, depicted by NPMG. The inefficiency is due to the single shot update of transmit beamformers at the start of the iterations. We also show the performance results when $N = 8$ pairs coexist on the same figure. In this case, the global centralized solution is not tractable, because the search space includes 16^8 possible beamforming vector combinations. Therefore, the performances of only COPMA and NPMG are shown in this case. For $N = 4$ and $N = 8$ users, 99% and 90% of the gain from using COPMA algorithm is realized within the first 3 and 20 iterations respectively, although further improvement results from more iterations. For $N = 4$, the existence of NE in both COPMA and NPMG are corroborated by the convergence of curves in Fig. 2. For $N = 8$, final convergence of COPMA requires more than 100 iterations, however further iterations result in very small decreases in the total transmit power.

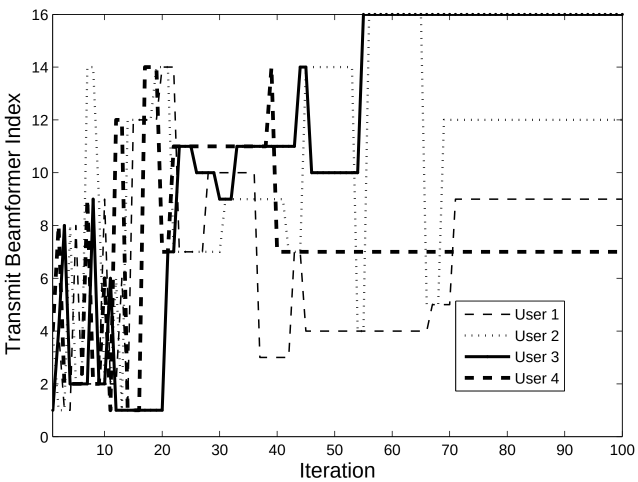

Fig. 3. Transmit beamformer indexes versus iteration in COPMA with $N = 4$, $T = 3$ and $\Upsilon = 16$.

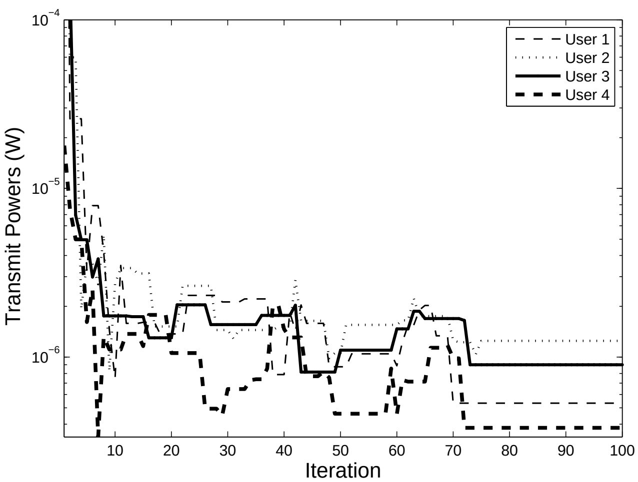

Fig. 4. Transmit powers versus iteration in COPMA with $N = 4$, $T = 3$ and $\Upsilon = 16$.

Fig. 3 and Fig. 4 depict the trajectories of transmit beamformer selection indices and power trajectories in COPMA for each user in one of the network configuration for $N = 4$. Each user updates its own transmit beamformer and power levels iteratively following COPMA algorithm, until the optimum NE point is reached. Note that when the transmit beamformer index vector and power levels converge in Fig. 3 and Fig. 4, the corresponding overall total transmit power obtained by COPMA is shown in Fig. 2.

VI. Conclusion

In this paper, we have considered joint power control and beamforming in MIMO ad-hoc networks under constant QoS requirements. We proposed and compared the performances of iterative cooperative and noncooperative algorithms. COPMA with high probability of convergence is studied for the cooperative scheme. For the non-cooperative case, we proposed NPMG where all the transmit beamformers are updated at the start of the iteration and then power control is performed. Numerical results corroborate the convergence results of NPMG and COPMA, and the effectiveness of the COPMA's performance in terms of comparison with the centralized case.

References

[1] I. E. Telatar, "Capacity of multi-antenna gaussian channel," *European Transactions on Telecommunications*, vol. 10, p. 589595, November/December 1999.

[2] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications a key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, pp. 198– 218, February 2004.

[3] D. J. Love and R. W. Heath, "Grassmannian beamforming for multiple-input multiple-output wireless systems," *IEEE Transactions on Information Theory*, vol. 49, pp. 2735–2747, October 2003.

[4] M. C. Bromberg and B. G. Agee, "Optimization of spatially adaptive reciprocal multipoint communication networks," *IEEE Transactions on Communications*, vol. 51, pp. 1254–1257, August 2003.

[5] S. Ye and R. S. Blum, "Optimized signaling for MIMO interference systems with feedback," *IEEE Transactions on Signal Processing*, vol. 51, pp. 2839–2848, November 2003.

[6] R. Iltis, S. Kim, and D. Hoang, "Noncooperative iterative MMSE beamforming algorithms for ad hoc networks," *IEEE Transactions on Communications*, vol. 54, pp. 748–759, April 2006.

[7] H. Sampath, P. Stoica, and A. Paulraj, "Generalized linear precoder and decoder design for MIMO channels using the weighted MMSE criterion," *IEEE Transactions on Communications*, vol. 49, pp. 2198–2206, December 2001.

[8] D. P. Palomar, J. M. Cioffi, and M. A. Lagunas, "Joint tx-rx beamforming design for multicarrier mimo channels: a unified framework for convex optimization," *IEEE Transactions on Signal Processing*, vol. 51, pp. 2381–2401, September 2003.

[9] G. Arslan, M. F. Demirkol, and Y. Song, "Equilibrium efficiency improvement in mimo interference systems: a decentralized stream control approach," *IEEE Transactions on Wireless Communications*, vol. 6, pp. 2984–2993, August 2007.

[10] D. Fudenberg and J. Tirole, *Game Theory*. Cambridge, MA: MIT Press, 1991.

[11] R. D. Yates, "A framework for uplink power control in cellular radio systems," *IEEE Journal on Selected Areas in Communications*, vol. 13, pp. 1341– 1347, September 1995.