Coalitional Games in Cooperative Radio Networks

Suhas Mathur, Lalitha Sankaranarayanan and Narayan B. Mandayam
WINLAB Dept. of Electrical and Computer Engineering
Rutgers University, Piscataway, NJ
{suhas, lalitha, narayan}@winlab.rutgers.edu

***Abstract*— The framework of coalitional game theory is used to study the formation of coalitions in an M-link wireless interference channel when either the transmitters or the receivers cooperate. It is shown that the stable coalition structure, i.e., the coalition structure for which users have no incentives to defect, depends upon the apportioning scheme chosen to distribute the cooperative rate gains between the coalition members. Under both a flexible (*transferable*) and fixed (*non-transferable*) apportioning scheme, the stable coalitions formed by cooperating receivers are presented. The problem of determining stable coalitions for the case of cooperating transmitters is discussed.**

I. Introduction

User-cooperation in wireless networks promises to leverage the broadcast nature of the wireless medium to provide improved sharing of power and bandwidth resources. However, when rational users are allowed to cooperate it is necessary to examine whether the participation of all users in a cooperative protocol can be taken for granted. Users may be unwilling to spend their limited resources in aiding cooperation in a wireless network. A further disincentive to cooperation may result from the rules by which the gains from cooperation are distributed to participating users. If users can do better by cooperating only selectively, they may form *coalitions* that are closed to cooperation for users outside the group.

We address this issue by studying two essential questions related to cooperative communications: Does cooperation always result in optimal use of the power and bandwidth resources of the network? Further, if users are allowed to form coalitions, does it always result in a stable coalition structure? We use the interference channel model to study receiver and transmitter cooperation. We find that the emergent cooperative behavior depends upon the way in which the gains from cooperation are apportioned between cooperating users and that the resulting conflicts of users' interests can be quantified using the tools of coalitional game theory.

In Section II we provide a brief overview of coalitional games. In Section III we describe the interference channel model. In Section IV we describe the receiver cooperation problem and we provide a summary of our results. In Section V we study receiver cooperation in a multiaccess channel using linear multiuser detection. In Section VI, we use the interference channel model to describe the transmitter cooperation problem. We conclude in Section V along with some future directions of interest.

II. Overview of Coalitional Game Theory

In this section we briefly review aspects of coalitional game theory [1] in the context of our problem. We consider coalitional games in which every coalition is ascribed a single number, interpreted as the total payoff available to the coalition or the *value* of the coalition. The share of the payoff received by players in a coalition is called a *payoff vector*. When there are no restrictions on how this payoff may be apportioned between members, the game is said to have *transferable utility* (TU).

Definition 1: A coalitional game with transferable utility $\langle \mathcal{S}, v \rangle$ is defined through

- a finite set of players $\mathcal{S}$,
- a function v that associates with every non-empty subset $\mathcal{G}$ (a coalition) of $\mathcal{S}$, a real number $v(\mathcal{G})$ (the value of $\mathcal{G}$) with $v(\{\phi\}) = 0$

In general, the value of a coalition may not lend itself to arbitrary apportioning and the nature of the game may place restrictions on the ways that value can be apportioned. The game is then said to have *non-transferable utility* (NTU).

Definition 2: A coalitional game in which the value of a coalition $v(\mathcal{G})$ is not influenced by the actions of players outside that coalition is referred to as a coalitional game in *characteristic function form*.

In the following sections we show that receiver cooperation in an interference channel results in coalitional games in characteristic function form while transmitter cooperation does not. The advantage of having a game in this form is that the behavior of any coalition of players can be completely characterized without having to worry about the responses of players outside the coalition. The number of possible coalition structures (partition of players into coalitions) in a coalitional game with TU grows exponentially with the number of players. In fact, finding the optimal (by *optimal* we mean that coalition structure which maximizes the sum of the payoffs of all players) coalition structure is an $\mathcal{NP}$-complete problem [2]. However, this search can be greatly simplified if the game has the following properties.

Definition 3: A coalitional game with transferable utility is said to be *superadditive* if for any two disjoint coalitions $\mathcal{G}_1, \mathcal{G}_2 \subseteq S$, $v(\mathcal{G}_1 \cup \mathcal{G}_2) \geq v(\mathcal{G}_1) + v(\mathcal{G}_2)$.

Definition 4: A coalitional game with transferable utility is said to be *cohesive* if the value of the coalition formed by the set of all players $\mathcal{S}$ (the *grand coalition*) is at least as large as the sum of the values of any partition of $\mathcal{S}$, i.e.

$$v(\mathcal{S}) \geq \sum_{k=1}^{K} v(\mathcal{S}_k) \tag{1}$$

for every partition $\{\mathcal{S}_1, \ldots, \mathcal{S}_K\}$ of $\mathcal{S}$.

A superadditive coalitional game is cohesive but not vice-verse. A transferable utility game that is cohesive has the grand coalition as the optimal coalition structure [1]. A cohesive TU game therefore lends itself to simpler analysis since we only need to study the stability of the grand coalition.

Definition 5: For any coalition $\mathcal{G}$, a vector $\underline{x}_{\mathcal{G}} = (x_m)_{m\in\mathcal{G}}$ of real numbers is a $\mathcal{G}$-*feasible payoff vector* if $x(\mathcal{G}) = \sum_{m\in\mathcal{G}} x_m = v(\mathcal{G})$. The $\mathcal{S}$-feasible payoff vector is referred to as a *feasible payoff profile*.

Of all possible coalition structures that can form, the coalitions that are stable, that is, those in which no set of players (either from within or from across coalitions) have incentives to defect, are of most interest. The set of such stable coalitions comprises a *core*, defined formally below.

Definition 6: The core, $C(v)$, of a coalitional game with transferable payoff, $\langle \mathcal{S}, v\rangle$, is the set of feasible payoff profiles $\underline{x}_{\mathcal{S}}$ for which there is no coalition $\mathcal{G} \subset \mathcal{S}$ and a corresponding $\mathcal{G}$-feasible payoff vector $\underline{y}_{\mathcal{G}} = (y_m)_{m\in\mathcal{G}}$ such that $y_m > x_m$ for all $m \in \mathcal{G}$.

We are interested in determining whether cooperation between users communicating on wireless channels results in optimal coalition structures that are also stable. Such solutions represent a win-win situation for all the users in the system as well as from the point of view of efficient use of the shared spectrum. With these goals in mind, we next describe the interference channel model that we use for studying receiver cooperation and transmitter cooperation under the framework of TU coalitional games.

III. Interference Channel Model

We consider an interference channel of M communication links, each formed by a single transmitter-receiver pair, coexisting in the same shared spectrum [3]. We assume that every transmitter has a single antenna. X_i is the transmit signal of link i and Y_i is the received signal at the corresponding receiver. We denote by $\mathcal{S} = \{1, 2, ..., M\}$ the set of all links and write $\mathbf{X}_{\mathcal{G}} = \{X_i : i \in \mathcal{G}\}$ for all $\mathcal{G} \subseteq \mathcal{S}$ and $\mathcal{G}^c$ as the complement of $\mathcal{G}$ in $\mathcal{S}$. We consider an additive white Gaussian noise channel with fixed channel gains. The received signal at the receiver of link i is given by

$$Y_i = \sum_{k=1}^{M} h_{i,k} X_k + Z_i, \tag{2}$$

where $h_{i,k}$ is the channel gain between the transmitter of link k and the receiver of link i and is assumed to be a constant known to all transmitters and receivers. The noise entries $Z_i \sim \mathcal{CN}(0,1)$, are independent, circularly symmetric, complex Gaussian random variables with zero mean and unit variance, for all i. The power constraint at the i^{th} transmitter is

$$E|X_i|^2 \leq P_i \quad i \in \mathcal{S} \tag{3}$$

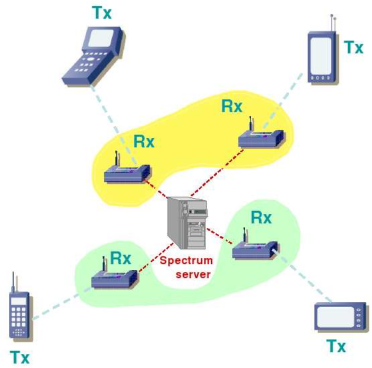

Fig. 1. An interference channel with M transmit-receive links. Receiver cooperation turns the channel into a SIMO-MAC.

We assume that the transmitters employ Gaussian signaling subject to the power constraint in (3). The capacity region of the interference channel that results when links do not cooperate is, in general, unknown.

IV. Receiver Cooperation in an IC: TU

Here, we study the formation of stable coalitions when receivers in an interference channel are allowed to cooperate by jointly decoding their received signals. We assume that the receivers that choose to cooperate can communicate with one another via a central spectrum server and that the transmitters do not cooperate. This models a variety of practical networks operating in the unlicensed bands where the receivers can communicate via a backbone network while the wireless transmitters, in general, cannot. For the input signaling considered, a coalition of cooperating receivers treats signals from transmitters outside the coalition as additive white Gaussian noise. Such a coalition can be modeled as a single-input, multiple-output multiple access channel (SIMO-MAC), the capacity region of which is known [4] and is achieved by the Gaussian input signaling chosen.

We define the value $v(\mathcal{G})$ of a coalition of receivers $\mathcal{G}$ as the maximum sum-rate achievable by the links corresponding to receivers in $\mathcal{G}$. For the channel model considered, $v(\mathcal{G})$ is then the maximum mutual information between the transmitters and receivers in $\mathcal{G}$ given as

$$v(\mathcal{G}) = \max_{\underline{R}_{\mathcal{G}} \in \mathcal{C}_{\mathcal{G}}} \sum_{i\in\mathcal{G}} R_i = \max_{p_{X_{\mathcal{G}}}} I(\mathbf{X}_{\mathcal{G}}; \mathbf{Y}_{\mathcal{G}}), \tag{4}$$

where $\underline{R}_{\mathcal{G}} = (R_i)_{i\in\mathcal{G}}$ is the vector of rates for links in $\mathcal{G}$ and $\mathcal{C}_{\mathcal{G}}$ is the capacity region of the SIMO-MAC formed by the users in $\mathcal{G}$. Depending on its allocated share of $v(\mathcal{G})$, a receiver may decide to break away from the coalition $\mathcal{G}$ and join another coalition where it achieves a greater rate. We model the problem of determining the stable coalitions and the resulting rate allocations for the interference channel as a coalitional game with transferable utility and refer to this game as the *receiver cooperation interference channel game* [5]. We now state our main results (see [5] for detailed proofs).

Theorem 7: The grand coalition maximizes spectrum utilization in the receiver cooperation interference channel game.

Theorem 8: The receiver cooperation interference channel game with transferable utility has a non-empty core.

The core of the receiver cooperation interference channel game being non-unique, a natural question that arises is what allocation of rates must be chosen from all the payoff profiles in the core and whether there are any *fair* means of arriving at such an allocation. We address this question by treating rate allocation as a bargaining problem between M users. We propose a Nash bargaining solution NBS [6] and a proportional fair solution [7] as a means to choose two specific rate allocations that belong to the core. The NBS maximizes the product of the rate gains via cooperation achieved by each user over their interference channel performance [5]. This allows the apportioning of the sum-rate achieved in a manner that gives users credit for their individual worth, where each user's individual worth is simply the rate it can achieve when it does not participate in cooperation at all.

V. Receiver cooperation using Linear Multiuser Detectors: NTU

We consider receiver cooperation under a non-transferable utility allocation for a multiaccess channel using linear multiuser detection. We assume that the transmitters do not cooperate while the receivers decide to form linear multiuser detector coalitions to maximize their payoffs. We model the payoff achieved by each user by its achieved SINR. We observe that the rate achieved by a user is a monotonic increasing function of the SINR and thus, maximizing the SINR is equivalent to maximizing the rate. In particular, we consider the decorrelating receiver [8] and the MMSE receiver [9] in the context of the MAC.

We consider a MAC channel with M users communicating with one base station (BS) in a BPSK modulated, synchronized CDMA system with no power control. We denote the set of all users by $\mathcal{S} = \{1, \ldots, M\}$. Users are assumed to have been assigned signature sequences such that the correlation between the sequences of any two users is ρ. The received signal at the BS is given by

$$y(t) = \sum_{i=1}^{M} \sqrt{P} h_i b_i s_i(t) + \sigma n(t), \quad t \in [0, T] \tag{5}$$

where P is the common transmit power of each user, h_i is channel gain from user i to the BS and is assumed known at the BS, $b_i \in \{+1, -1\}$ is the bit transmitted by user i in the bit interval $[0, T]$, $s_i(t)$ is the signature sequence of user i and $n(t)$ is an additive white Gaussian noise process with unit

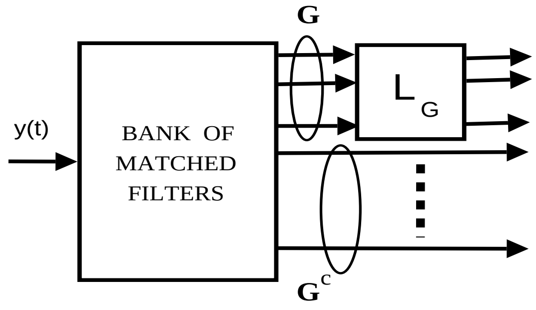

Fig. 2. A coalition $\mathcal{G}$ of users formed by a multiuser detector $\mathbf{L}_{\mathcal{G}}$

variance. The received signal in (5) is filtered through a bank of filters matched to the M signature sequences resulting in the $M \times 1$ received signal vector $\mathbf{y} \in \mathbb{R}^M$ [10]

$$\mathbf{y} = \mathbf{RAb} + \mathbf{n}, \tag{6}$$

where $\mathbf{R} \in \mathbb{R}^{M \times M}$ is the cross correlation matrix, $\mathbf{A}$ is a diagonal matrix of size $M \times M$ containing the received amplitudes of the M users, $\mathbf{b}$ is an $M \times 1$ vector containing their transmitted bits and $\mathbf{n} \in \mathbb{R}^M$ is a Gaussian random vector with zero mean and covariance matrix $\sigma^2 \mathbf{R}$. In a traditional linear MUD, the received vector $\mathbf{y}$ is put through a linear transformation $\mathbf{L}$ and the resulting vector $\mathbf{Ly}$ is used for decoding the bits of the users. For the decorrelator, $\mathbf{L} = \mathbf{R}^{-1}$ and for the MMSE detector, $\mathbf{L} = (\mathbf{R} + \sigma^2 \mathbf{A}^{-2})^{-1}$. In the coalitional game formulated here, we assume that users form coalitions of multiuser detectors as shown in figure 2.1. Let $\mathcal{G} \subset \mathcal{S}$ be such a coalition. Then the received signal vector for this coalition can be written as

$$\mathbf{y}_{\mathcal{G}} = \mathbf{R}_{\mathcal{G}} \mathbf{A}_{\mathcal{G}} \mathbf{b}_{\mathcal{G}} + \widetilde{\mathbf{R}}_{\mathcal{G}^c} \mathbf{A}_{\mathcal{G}^c} \mathbf{b}_{\mathcal{G}^c} + \mathbf{n}_{\mathcal{G}}, \tag{7}$$

where $\mathbf{R}_{\mathcal{G}} \in \mathbb{R}^{|\mathcal{G}| \times |\mathcal{G}|}$ is the cross correlation matrix of the users in $\mathcal{G}$, $\mathbf{A}_{\mathcal{G}} \in \mathbb{R}^{|\mathcal{G}| \times |\mathcal{G}|}$ is a diagonal matrix containing the received amplitudes of users in $\mathcal{G}$, $\mathbf{b}_{\mathcal{G}}$ is the vector of bits sent by users in $\mathcal{G}$ and $\mathbf{n}_{\mathcal{G}} \in \mathbb{R}^{|\mathcal{G}|}$ is a random Gaussian vector with zero mean and covariance matrix $\sigma^2 \mathbf{R}_{\mathcal{G}}$. The matrix $\widetilde{\mathbf{R}}_{\mathcal{G}^c}$ is of dimension $|\mathcal{G}| \times |\mathcal{G}^c|$ and contains the cross correlations between the the signature sequences of users in $\mathcal{G}$ and those of users in $\mathcal{G}^c$, i.e., $(\widetilde{R}_{\mathcal{G}^c})_{ij} = \rho$, $\forall i = 1, \ldots, |\mathcal{G}|$ and $j = 1, \ldots, M - |\mathcal{G}|$, $\mathbf{A}_{\mathcal{G}^c}$ is a $|\mathcal{G}^c| \times |\mathcal{G}^c|$ diagonal matrix containing the amplitudes of users not in $\mathcal{G}$ and $\mathbf{b}_{\mathcal{G}^c}$ is the $|\mathcal{G}^c| \times 1$ vector containing their transmitted bits. The linear MUD for the users in $\mathcal{G}$ puts the vector $\mathbf{y}_{\mathcal{G}}$ in (7) through the linear transformation $\mathbf{L}_{\mathcal{G}}$, where $\mathbf{L}_{\mathcal{G}} = \mathbf{R}_{\mathcal{G}}^{-1}$ for the decorrelating detector and $\mathbf{L}_{\mathcal{G}} = (\mathbf{R}_{\mathcal{G}} + \sigma^2 \mathbf{A}_{\mathcal{G}}^{-}2)^{-1}$ for the linear MMSE detector. Users within a coalition benefit from the interference suppression offered by their MUD. Since the SINR achieved by a user in a MUD cannot be shared with other users in the coalition, we model this scenario as a coalitional game with non-transferable utility.

1) Decorrelating Receiver: We know that the decorrelating receiver will nullify all interference from users that are part of the same coalition, at the price of enhancing the noise and the interference from users outside the coalition. It can be shown that the SINR of user i in a decorrelating detector coalition $\mathcal{G}$

is given by [11]

$$x_i(\mathcal{G}) = \text{SINR}_i^{decorr}(\mathcal{G}) \quad (8)$$
$$= \frac{P_i}{\frac{\sigma^2}{1-\rho}\frac{1+\rho(|\mathcal{G}|-2)}{1+\rho(|\mathcal{G}|-1)} + \left[\frac{\rho}{1+\rho(|\mathcal{G}|-1)}\right]^2 \sum_{j\in\mathcal{G}^c} P_j},$$
$$\forall\ i \in \mathcal{G},$$

where $P_k = h_k^2 P$ is the received power of user k at the BS.

Theorem 9: In the decorrelating detector MAC game, the grand coalition is stable and sum-rate maximizing in the high SNR regime.

Proof: See [12] ■

In general, however, there is no guarantee that the grand coalition of users should form or that the stable coalition structure should be the one that maximizes sum-rate

2) Linear MMSE Receiver: Unlike the decorrelating receiver, the linear MMSE receiver attacks both the noise and the interference and for a coalition $\mathcal{G}$, applies the linear transformation $\mathbf{L}_\mathcal{G} = [\mathbf{R}_\mathcal{G} + \sigma^2\mathbf{A}_\mathcal{G}^2]^{-1}$. It can be shown that the SINR $\gamma_i(\mathcal{G})$ of a user in a linear MMSE detector coalition $\mathcal{G}$ is given by [11]

$$\gamma_i(\mathcal{G}) = \frac{[(\mathbf{L}_\mathcal{G}\mathbf{R}_\mathcal{G})_{ii}]^2 P_i}{\begin{pmatrix} \sigma^2(\mathbf{L}_\mathcal{G}\mathbf{R}_\mathcal{G}\mathbf{L}_\mathcal{G})_{ii} + \rho^2[(\mathbf{L}_\mathcal{G}\mathbf{U}_\mathcal{G})_i]^2 \sum_{j\notin\mathcal{G}} P_j \\ + \sum_{j\in\mathcal{G}, j\neq i} [(\mathbf{L}_\mathcal{G}\mathbf{R}_\mathcal{G})_{ij}]^2 P_j \end{pmatrix}}, \quad (9)$$

where the second and third terms in the denominator of the above expression represent the effective interference to user i from users outside the coalition $\mathcal{G}$ and that from other users in the MMSE coalition respectively. Here $\mathbf{U}_\mathcal{G}$ is the $|\mathcal{G}|\times 1$ vector $\mathbf{U}_\mathcal{G} = [1\ldots 1]^T$. Since minimizing the mean square error is equivalent to maximizing the SINR [9], it is straightforward to show that the grand coalition is always stable and is also sum-rate maximizing, as long as the mapping of SINR to rate is monotonically increasing (non decreasing).

VI. Transmitter Cooperation

We use the interference channel model described in section III and consider the case when the transmitters cooperate. For this case, we assume that the receivers of all links are connected by a side channel or a spectrum server and jointly decode their received signals. We therefore view the receivers as an array of distributed antennas. Cooperating transmitters are assumed to have non-causal knowledge of the desired transmit signals of all other transmitters. For the Gaussian channel model considered, this implies that the transmitters in a coalition cooperate by jointly choosing their transmit covariance matrices. Transmitters belonging to different coalitions do not share information and transmit statistically independent signals. We assume that each transmitter has an individual power constraint given by (3). The transmitters are free to join a coalition of their choice. The channel resulting from this type of cooperation can be modeled as a MIMO-MAC (multiple-input multiple-output, multiple access channel). Under the

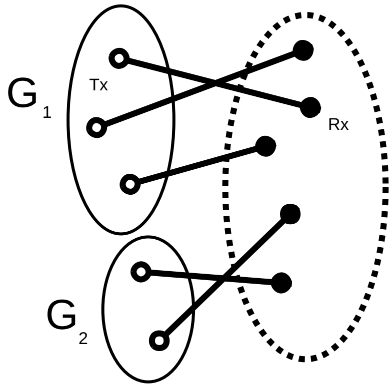

Fig. 3. Transmitter cooperation viewed as a coalitional game.

assumption of transferable utility, we seek to determine the stable sum-rate maximizing coalition structures formed.

The $M \times 1$ vector of received signals at the M receivers is given by

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{Z} \quad (10)$$

where $\mathbf{X}$ is the $M\times 1$ vector containing the channel inputs of the M transmitters, $\mathbf{H}$ is an $M\times M$ matrix whose $(i,j)^{th}$ element is the channel gain from transmitter j to receiver i as defined in Section III, and $\mathbf{Z}$ is a vector of size $M\times 1$ whose i^{th} entry is the noise at receiver i as described in Section III.

We define the value of a coalition $\mathcal{G}$ of transmitters as the maximum sum-rate achieved by the transmitters in $\mathcal{G}$. Thus, for Gaussian signaling at the transmitters, we write

$$v(\mathcal{G}) = \max_{\mathbf{Q}_\mathcal{G}:\mathbf{Q}_{ii}\leq P_i} I(X_\mathcal{G}; Y_\mathcal{S}) \quad (11)$$

where

$$\mathbf{Q}_\mathcal{G} = E\left[\mathbf{X}_\mathcal{G}\mathbf{X}_\mathcal{G}^\dagger\right] \quad (12)$$

is the covariance matrix of transmitters in $\mathcal{G}$ subject to (3).

The value $v(\mathcal{G})$ in (11) is maximized over the input covariance matrix $\mathbf{Q}_\mathcal{G}$; however, the users in $\mathcal{G}$ suffer interference from those in $\mathcal{G}^c$ and thus the value $v(\mathcal{G})$ depends on the signaling of those users. This implies that the transmitter cooperation coalitional game cannot be analyzed in characteristic function form because the value of a coalition depends on the actions of users outside that coalition. Hence, any coalition of transmitters $\mathcal{G}$ cannot make a decision about rejecting a proposed apportioning of value because it cannot determine with certainty, the payoff it would achieve if it broke away. Analyzing the transmitter cooperation game in such a setting is a difficult problem.

It is possible, however, to convert the above game to characteristic function form. This could be done, for example, by altering the definition of the value of a coalition to mean the maximum sum-rate it can achieve when it faces the worst possible interference from users outside it. A similar approach has been adopted in [13] where the authors study the formation of coalitions in the Gaussian multi-access channel when the interfering transmitters bargain for rates by threatening to transmit worst case jamming noise. This approach makes $v(\mathcal{G})$

independent of the true actions of players outside of $\mathcal{G}$ by assuming that whenever any group of transmitters attempts to break away as a coalition $\mathcal{G}$ it will be deterred by the threat of all users in $\mathcal{G}^c$ to collectively transmit a signal that provides worst case jamming to the coalition $\mathcal{G}$. We use this approach to further analyze the transmitter cooperation game in [14].

VII. Conclusions and Future Work

In this paper, we have proposed a convenient framework for analyzing whether cooperation in a given wireless network is likely to succeed. The ideas behind cohesiveness and the core of a coalitional game relate directly to efficiency and stability of cooperation respectively.

It is of particular interest to study the transmitter cooperation game that would result [14] if users in a multiaccess channel were allowed to cooperate using the user-cooperation diversity model [15] proposed by Sendonaris *et al*. In this model, transmitters can help each other by partially decoding each others' messages and using part of their limited power budget to transmit these messages after re-encoding them. Since this type of cooperation does not permit arbitrary sharing of the sum-rate achieved by a group of users, we must model this as a game with non-transferable utility wherein the value of each coalition is represented by a set function $v(\mathcal{G})$ representing the set of all possible rate vectors achievable by that coalition. Finally, we remark that coalitional game theory can be used to analyze cooperation in a variety of other network models and specific cooperative schemes.

References

[1] M. Osborne and A. Rubenstein, *A Course in Game Theory*. MIT Press, 1994.

[2] T. Sandholm, K. Larson, M. Anderson, O. Shehory, and F. Tohme, "Coalition structure generation with worst case guarantees," *Artificial Intelligence*, vol. 10, pp. 209–238, July 1999.

[3] A. B. Carleial, "Interference channels," *IEEE Trans. Inform. Th.*, vol. 24, no. 1, pp. 60–70, Jan. 1978.

[4] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. Telecommunications*, vol. 10, pp. 585–595, Nov. 1999.

[5] S. Mathur, L. Sankaranarayanan, and N. Mandayam, "Coalitional games in gaussian interference channels," *International Symposium on Information Theory, Seattle, Washington*, July 2006.

[6] J. F. Nash, "The bargaining problem," *Econometrica*, vol. 18, no. 2, pp. 155–162, Apr. 1950.

[7] F. Kelly, "Charging and rate control for elastic traffic," *Euro. Trans. Telecommun*, vol. 8, pp. 33–37, Jan. 1997.

[8] R. Lupas and S. Verdu, "Linear multiuser detectors for synchronous code division multiple access channels," *IEEE Trans. Inform. Theory*, vol. 41, no. 4, pp. 1083–1096, Jan. 1989.

[9] U. Madhow and M. Honig, "MMSE interference suppression for direct sequence spread spectrum CDMA," *IEEE Transactions on Communications*, vol. 42, no. 12, pp. 3178–3188, Dec. 1994.

[10] S. Verdu, *Multiuser Detection*. Cambridge University Press, 1998.

[11] Y. Li and A. Ephremides, "Linear multiuser detectors for incompletely known symmetric signals in CDMA systems," *IEEE Trans. Inform. Theory*, vol. 50, no. 6, pp. 1026–1040, June 2004.

[12] S. Mathur, L. Sankaranarayanan, and N. Mandayam, "Coalitional games in receiver cooperation for spectrum sharing," in *Conf. on Inf, Sciences and Sys.*, Princeton, NJ, Mar. 2006.

[13] R. La and V. Anantharam, "A game-theoretic look at the Gaussian multiaccess channel," *Advances in Network Information Theory, Proceedings of the March 2003 DIMACS workshop on Network Information Theory, DIMACS series in Discrete Mathematics and Theoretical Computer Science*, vol. 66, pp. 37–42, Nov. 2003.

[14] S. Mathur, L. Sankaranarayanan, and N. Mandayam, "Coalitional games in cooperative networks," *Journal paper, to be submitted to Trans. Commun.*, 2006.

[15] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - part I: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.