Competitive Resource Sharing Based on Game Theory in Cooperative Relay Networks

Guopeng Zhang, Li Cong, Liqiang Zhao, Kun Yang, and Hailin Zhang

ABSTRACT—This letter considers the problem of resource sharing among a relay and multiple user nodes in cooperative transmission networks. We formulate this problem as a sellers' market competition and use a noncooperative game to jointly consider the benefits of the relay and the users. We also develop a distributed algorithm to search the Nash equilibrium, the solution of the game. The convergence of the proposed algorithm is analyzed. Simulation results demonstrate that the proposed game can stimulate cooperative diversity among the selfish user nodes and coordinate resource allocation among the user nodes effectively.

Keywords—Resource allocation, cooperative relay, game theory, Nash equilibrium.

I. Introduction

The basic idea of cooperative transmission is to allow nodes in a network to help relay information for each other so as to exploit the inherent spatial diversity which is available in the relay channels. Since relaying represents a cost of resource (energy or bandwidth), in commercial networks, the following two basic issues must be dealt with: when to relay, that is, when it is beneficial to use the relay, and how to relay, that is, how the relay should allocate its resource among the user nodes.

Most previous work on resource allocation for cooperation transmission is based on centralized control. To tackle the two problems just mentioned in a distributed way, game theory is a natural and powerful tool which studies how selfish nodes interact and cooperate with each other. In this area, Zhaoyang [1] studied a symmetric relay model in which each node can act as both a source and a relay based on the cooperative game theory. Beibei [2] proposes a Stackelberg game to perform the resource allocation. The game is formulated as a buyers' market competition where multiple relays compete with each other in terms of price to gain the highest profit from offering power to a single user.

Unlike [1] and [2], we study an asymmetric relay model by considering the problem of how a relay should coordinate resource allocation among multiple competing users. We formulate this problem as a sellers' market competition and use a pricing-based noncooperative game to jointly consider the benefits of the relay and the users.

II. System Model and Problem Formulation

An asymmetric relay model is illustrated in Fig. 1. A transmitter–receiver pair including a source node s_i and destination node d_i is referred to as a user i. A node r closer to the destination nodes is designated as the *potential relay*.

Without the loss of generality, we employ the amplify-and-forward (AF) cooperation protocol in the system and consider basing the system on frequency-division multiple access (FDMA). Each node is allocated w Hz bandwidth for transmission. The relay r is willing to share portions of its bandwidth with the users for cooperative transmission. The energy required to relay a packet is assumed to be constant as in [2] and [3].

Let $\mathbf{I}=\{1,\cdots, N\}$ denote the set of users currently in the system. If relay r decides to share bandwidth w_i ($0\le w_i\le w$)

Manuscript received Oct. 17, 2008; revised Dec. 16, 2008; accepted Dec. 24, 2008.

This work was supported by the National Natural Science Fund Plan of China under Grant No. 60772317 and the Natural Science Basic Research Plan in Shaanxi Province of China under Grant No. 2006F30.

Guopeng Zhang (phone: + 86 29 88201357 8509, email: brahms_zgp@163.com), Li Cong (email: congli8462@163.com), Liqiang Zhao (email: lqzhao@mail.xidian.edu.cn), and Hailin Zhang (hailinzhang@mail.xidian.edu.cn) are with the State Key Laboratory of Integrated Services Networks, Xidian University, Shaanxi, China.

Kun Yang (email: KunYang@essex.ac.uk) is with the Department of Electronic Systems Engineering, University of Essex, Colchester, UK.

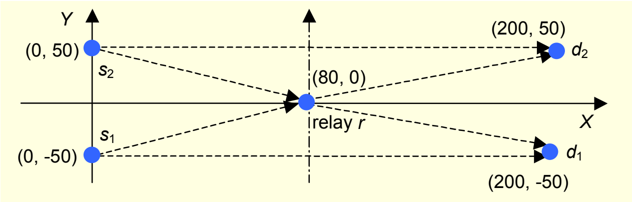

Fig. 1. Cooperative communication system model.

with user i, it will relay w_i of the data originating from source s_i. That means w_i of source s_i's data will be transmitted in a cooperative manner, and the remaining w-w_i parts can only be directly transmitted to destination d_i without any relaying.

Cooperation refers to a real cost of resource expenditure, and the relay could cover this cost by selling its bandwidth to the users. Define user i's strategy as the bandwidth size, w_i, that he wants to buy from the relay. The pricing function used by the relay to charge the users is defined as in [5] as

$$c(\mathbf{W}) = a + b(\sum_{i=1}^{N} w_i), \quad (1)$$

where a and b are non-negative constants, and $\mathbf{W}=\{w_1,\cdots, w_N\}$ denotes the set of strategies adopted by all users.

Given the current relaying price c, each selfish user prefers to maximize his benefit/utility by adjusting his strategy. Since price c depends on the strategies of all users, the resource competition between the users is actually a strategic game. We call it a cooperative transmission game (CTG).

A kind of utility function which can qualify the tradeoff between achieving high throughput and low energy consumption is defined as $u=T/p$ (bits per Joule) as in [4], where T and p are user's throughput and transmission power, respectively. Considering that the user transmits L bits of data packed into a frame of M ($M > L$) bits with bandwidth w, the throughput of the user can be expressed as $T=w\cdot f(\gamma)\cdot L/M$, where $f(\gamma)=[1\text{-}2\mathrm{BER}(\gamma)]^M$ is the efficiency function to approximate the probability of correct reception of a frame, $f(\gamma)=[1\text{-}\mathrm{BER}(\gamma)]^M$. The utility of a user is then interpreted as the number of data bits successfully received per joule of energy consumed.

Let γ_{s_i,d_i}, $\gamma_{s_i,r}$, and γ_{r,d_i} denote the SNRs of the wireless channels from source s_i to destination d_i, source s_i to relay r, and relay r to destination d_i, respectively. Then, the effective SNR of the AF cooperative channel of user i is given by $\gamma_{s_i,d_i}^{AF} = \gamma_{s_i,d_i} + \dfrac{\gamma_{s_i,r}\gamma_{r,d_i}}{1+\gamma_{s_i,r}+\gamma_{r,d_i}}$. Here, we define user i's utility function as

$$U_i = \left(T_{s_i,d_i}(p_i, w-w_i) + T_{s_i,d_i}^{AF}(p_i, w_i)\right)\big/ p_i - c\cdot w_i, \ \forall i \in \mathbf{I}, \quad (2)$$

where p_i is the transmit power of source s_i, $T_{s_i,d_i}(p_i, w-w_i) = (w-w_i) f(\gamma_{s_i,d_i}) L/M$ is the throughput derived from the direct transmission with bandwidth w-w_i, $T_{s_i,d_i}^{AF}(p_i, w_i) = w_i f(\gamma_{s_i,d_i}^{AF}) L/M$ is the throughput derived from the cooperative transmission helped by relay r with bandwidth w_i, and the last term, $c.w_i$, represents the payment paid by user i to relay r for resource consumption.

III. Solving the Game

The Nash equilibrium (NE) is the solution to a noncooperative game. At the NE, no user can increase his utility by choosing a different strategy, given the other users' best strategies.

Since the relaying price c is determined by the demand of all users, by substituting (1) into (2), we obtain

$$U_i = \frac{LW}{Mp_i} f(\gamma_{s_i,d_i}) + \frac{LW_i}{Mp_i}\Delta f(\gamma_{s_i,d_i}) - W_i\left(a + b(\sum_{j=1}^{N} W_j)^{\tau}\right), \quad (3)$$

where $\Delta f(\gamma_{s_i,d_i}) = f(\gamma_{s_i,d_i}^{AF}) - f(\gamma_{s_i,d_i})$.

Denote the set of best strategies of all users except user i as $\mathbf{W}_{-i}^{*} = \{w_1^{*},\cdots, w_{i-1}^{*}, w_{i+1}^{*},\cdots, w_N^{*}\}$. The best strategy of user i is given by

$$w_i^{*} = \arg\max_{w_i} U_i(w_i, \mathbf{W}_{-i}^{*}) \quad , \quad \forall i \in \mathbf{I}. \quad (4)$$

The best strategy profile of all the users, $\mathbf{W}^{*} = \{w_1^{*},\cdots, w_N^{*}\}$, is then the NE of the CTG.

To solve the CTG, we take the derivative of (3) with respect to w_i and set each derivative to 0. Then, we can have the following set of N equations:

$$\frac{\partial U_i}{\partial W_i} = \frac{L}{Mp_i}\Delta f(\gamma_{s_i,d_i}) - \left(a + b(\sum_{i=1}^{N} w_i)^{\tau} + w_i \tau b(\sum_{i=1}^{N} w_i)^{\tau-1}\right) = 0. \quad (5)$$

The solution of this equation set is the NE of the CTG. However, it can only be solved in a centralized manner since the strategies adopted by other users should be available to each user.

We developed a strategy update function to help users search the NE of the CTG in a distributed manner:

$$w_i(t+1) = w_i(t) + \theta_i w_i(t)\,\partial U_i(\mathbf{W})\big/\partial w_i(t), \quad (6)$$

where θ_i is the speed adjustment parameter of user i, $w_i(t)$ is the amount of bandwidth allocated to user i at time t, and $w_i(t+1)$ is the strategy that will be adopted by user i at time t+1.

This strategy update function is based on the marginal profit function borrowed from microeconomics, which only depends on the pricing information from the relay. The basic idea of the algorithm is that each user i's NE strategy should ensure $\partial U_i/\partial w_i=0$ at any time. Otherwise, if the bandwidth size allocated to user i is less than the optimal one at time t, $\partial U_i/\partial w_i$ will change from zero to positive. According to (6), user i will increase his/her demand at time t+1 to maximize his/her utility. If the bandwidth size allocated to user i is more than the optimal one at time t, the situation reverses. When the NE is reached, the condition $w_i(t+1)=w_i(t)=w_i^*$ is satisfied. This means user i cannot unilaterally improve his/her utility by choosing a different strategy. This analysis demonstrates that the users' strategies could converge to the NE if (6) is performed in a distributed and iterative manner.

IV. Simulation Results

A two-user simulated system is shown in Fig. 1. The path gain is set to $0.097/d^4$, and the noise level is 1×10^{-13} W. We assume all the nodes have the same transmit power of 0.1W, bandwidth size of 1 MHz, speed adjustment parameter with θ=0.01, and initial strategy with $w_i(0)=2\times10^4$ Hz. For the pricing function (1), we use a=0 and $b=10^{-5}$. The other parameters used in the simulations include L=64, M=80, and BER(γ)=1/2exp(-γ/2) for noncoherent frequency shift keying. We locate the two source nodes and the two destination nodes at (0, -50), (0, 50), (200, -50) and (200, 50). The x coordinate of relay r is fixed at 80, and its y coordinate is varied from -200 to 200. Let Y_r denote the x coordinate of relay r.

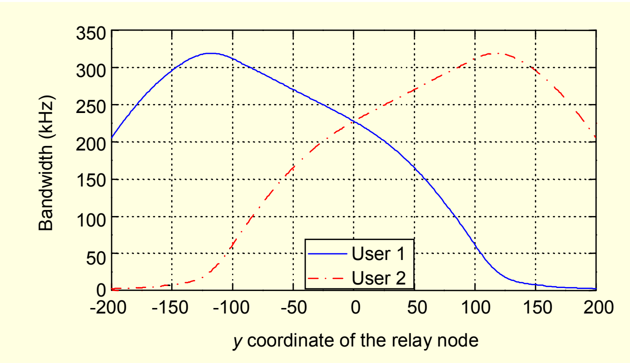

Fig. 2. Optimal bandwidth consumption of users when relay moves.

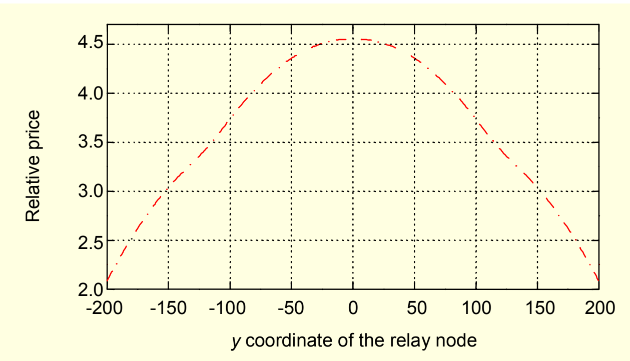

Fig. 3. Price of relay in various locations.

Figure 2 shows the optimal bandwidth size bought by the two users from the relay, while Fig. 3 depicts the relevant price charged by the relay at the NE. When $-200<Y_r<-125$, the bandwidth size bought by user 1 gradually increases to the maximum, whereas that of user 2 is almost 0. This is because, in this region, relay r is much closer to source s_1 than to source s_2. When $-125<Y_r<0$, the channel conditions from both source nodes to the relay become better. Although the service price continues increasing, user 2 would like to buy more bandwidth for cooperative transmission from the relay. When the relay moves to the coordinate (80, 0), a fair resource allocation between the users is achieved because both users have the same channel conditions to the relay. Also, the revenue of the relay reaches the maximum because the users' demand is highest at this point. When $0<Y_r<200$, the situation reverses.

Since the y coordinate of the relay represents the nodes' channel conditions, the two basic issues mentioned in section I, are addressed. Note that time-varying fading is not considered here. Otherwise, the x-axis represents the channel conditions instead of the y coordinate of the relay.

V. Conclusion

This letter has proposed a noncooperative game to perform the bandwidth allocation in FDMA-based cooperative relay networks. A distributed algorithm was also developed to find the Nash equilibrium of the game was used to solve the two basic problems of when and how to cooperate.

References

[1] Z. Zhang et al., "A Cooperation Strategy Based on Nash Bargaining Solution in Cooperative Relay Networks," *IEEE Trans. on Vehicular Technology*, vol. 57, no. 4, July 2008, pp. 2570-2577.

[2] B. Wang et al., "Distributed Relay Selection and Power Control for Multiuser Cooperative Communication Networks Using Buyer/Seller Game," *Proc. IEEE INFOCOM*, 2007, pp. 544-552.

[3] P. Marbach and Y. Qiu, "Cooperation in Wireless Ad Hoc Networks: A Market-Based Approach," *ACM Trans. on Networking*, vol. 13, no. 6, Dec. 2005, pp. 1325-1338.

[4] C.U. Saraydar et al., "Efficient Power Control via Pricing in Wireless Data Networks," *IEEE Trans. on Communications*, vol. 50, no. 2, Feb. 2002, pp. 291-303.

[5] D. Niyato et al. "Competitive Spectrum Sharing in Cognitive Radio Networks: A Dynamic Game Approach," *IEEE Trans. on Wireless Communications*, vol. 7, no. 7, July 2008, pp. 2651-2660.