A Cooperation Strategy Based on Nash Bargaining Solution in Cooperative Relay Networks

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***Abstract*—This paper proposes a cooperation strategy among rational nodes in a wireless cooperative relaying network as an effort to solve two basic problems, i.e., when to cooperate and how to cooperate. First, a symmetric system model comprising two users and an access point (AP) is presented. In this model, each user plays an equal role and acts as a source as well as a potential relay and has the right to decide the amount of bandwidth it should contribute for cooperation. Second, referring to the cooperative game theory, the above problems are formulated as a two-person bargaining problem. Then, a cooperation bandwidth allocation strategy based on the Nash bargaining solution is proposed, in which if a derived condition is satisfied, users will cooperatively work, and each will share a certain fraction of its bandwidth for relaying; otherwise, they will independently work. Simulation results demonstrate that when cooperation takes place, users benefit from the proposed strategy in terms of utility, and those with longer distance to the AP should spend more bandwidth to cooperate with others.**

***Index Terms*—Cooperative diversity, cooperative relay, game theory, Nash bargaining solution (NBS).**

I. Introduction

IN RECENT years, cooperative diversity [1], [2] has been proposed for applications in wireless networks to enlarge system coverage and increase link reliability. Generally, in such a network, all nodes are assumed to have their full willingness to relay data packets for others to achieve those objectives. However, in many applications, particularly in some commercial networks, the nodes usually represent different entities or serve for different service providers. Thus, their rational decisions, when facing problems such as whether to cooperate and to what an extent to cooperate, etc., depend on their own traffic load and available radio resources (e.g., energy, bandwidth, etc.). Extremely, a selfish user would exclusively occupy its resources to maximize its own benefit rather than to share them with others.

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The aforementioned problems bring difficulties in analyzing the behaviors of rational users in wireless networks. Recently, it has been shown that the game theory can be a potentially effective tool to solve this kind of problem and has been used in modeling the interactions in different network layers among users [3]. To tackle the decision-making problems on whether to cooperate and how to cooperate in wireless networks, many research works based on game theory have been published. In [4], a Generous Tit-for-Tat algorithm was proposed to help each node determine the willingness of cooperation based on its own historical statistics. In [5], a pricing algorithm that encourages forwarding among autonomous nodes through a reimbursing forwarding scheme was presented for multihop wireless networks. Based on the results given in [5], the authors of [6] studied a pricing game that stimulates cooperative diversity among selfish nodes in commercial wireless ad hoc networks.

However, both research results presented in [5] and [6] were based on an asymmetric model between source and relay. Their model consists of two users and an access point (AP). One user acts as a source and the other a potential relay, and both have the AP as their destination. However, the source has a chance to get the relay's help while the relay cannot benefit from the source since it never originates any data at all. That is, the roles of the two users are unequal in this model, making it hard to fully reveal the rational behaviors between users, particularly in cases when both users only have limited radio resources. Furthermore, the works in [4]–[6] are based on "noncooperative game theory," which are mainly focused on each user's individual utility rather than the utility of the entire system. In contrast, the schemes based on "cooperative game theory" [7]–[10] can achieve general pareto-optimal performance for cooperative games and, thus, maximize the entire system payoff while maintaining fairness.

Motivated by the aforementioned works, a symmetric system model, which similarly consists of two user nodes and an AP, except that each user can act as a source as well as a potential relay, is proposed in this paper. In this model, each user has the opportunity to share the other's resources (e.g., bandwidth and power) and seek the other user's cooperation to relay its data to obtain the cooperative diversity. The degree of cooperation depends on how much bandwidth the relay node is willing to contribute to the source for its data relaying. We first prove that the problem can be modeled as a "two-person bargaining problem," and then propose a cooperation strategy based on Nash bargaining solution (NBS), in which if a derived condition

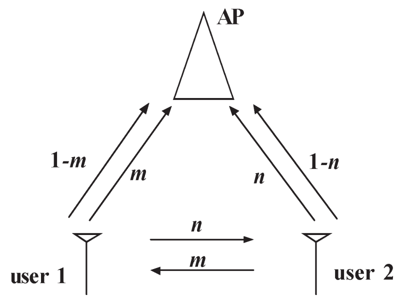

Fig. 1. Cooperative communication system model with two nodes and one AP.

is satisfied, users will cooperatively work, and each will share a certain fraction of its bandwidth for data relaying; otherwise, they will choose to independently work. This way, our proposed strategy can achieve an optimal system utility while keeping fairness among users. The analyzing results are demonstrated by computer simulations.

The rest of this paper is organized as follows. Section II presents the system model, and Section III defines the utility functions used in this paper. Section IV proposes a scheme based on cooperative game theory that helps nodes to find out their proper cooperation bandwidth based the NBS. Section V presents simulation results to demonstrate the effectiveness of the proposed scheme. Section VI discusses some implementation issues and the subjects for further study. This paper is concluded in Section VII.

II. System Model

A symmetric relay model is illustrated in Fig. 1, which differs from the asymmetric model given in [5] and [6]. This model includes two users (nodes) and one AP. Both nodes look on the AP as the final destination. We assume that the system is based on frequency division multiple access, and each user is allocated W hertz bandwidth for transmission. The antennas are omnidirectional, such that the data transmitted by user 1 can also be received by user 2, and *vice versa*. Part of the received signal will be relayed to the AP depending on the willingness of the receiving node. As illustrated in Fig. 1, user 1 is willing to split m fraction $(m \in [0,1])$ of its bandwidth to relay m fraction of the data originating from user 2, whereas user 2 is willing to use n fraction $(n \in [0,1])$ of its bandwidth to relay n fraction of the data originating from user 1. It means that user 1 can transmit its own data using only the remaining $1-m$ fraction of its bandwidth and in which only n fraction will be relayed by user 2. Note that only the data carried on that n fraction can be transmitted in a *cooperative* manner, i.e., can be combined with the amplify-and-forwarded replica from user 2 at the AP using maximal ratio combining to obtain the cooperative diversity. The remaining $1-m-n$ fraction of user 1's data will be directly transmitted to the AP without any relaying and, thus, having no diversity gain at all. Similarly, only m fraction of user 2's own data will be transmitted in a cooperative way, whereas the remaining $1-n-m$ fraction will be directly transmitted to the AP without any diversity.

For simplicity, we assume that each user will only relay the data originating from the other and will not relay the data originating from itself and then relayed by the other. This assumption avoids "cheating" between selfish users, increases the spectrum utilization, and reduces the signaling cost. Note that under this assumption, a relay can forward at most the same amount of data originating from the source itself, or, equivalently, in terms of bandwidth, for user 1, there is $m \leq 1-n$, whereas for user 2, $n \leq 1-m$, which both yield $m+n \leq 1$. Obviously, for a meaningful cooperation, both m and n should be nonnegative. Then, we have

$$\begin{cases} m \geq 0 \\ n \geq 0 \\ m+n \leq 1 \end{cases} \tag{1}$$

which will be used in the latter. From the introduction above, we know that the variables m and n reflect the rational decisions made by the users, and one user's choice of its parameter (i.e., user 1 determines m and user 2 determines n) will definitely affect the other user's choice. Both users expect an optimal tradeoff between their payout and payoff. How to solve this problem to achieve a win–win solution is what we are going to address next in particular.

III. Utility Function

Intuitively, the problem mentioned above is a two-person game, i.e., because each user's payoff is affected by the other user's decision parameter. When employing game theory to solve this kind of problem, we first have to understand a very important concept, i.e., utility actually reflects a user's payoff. At present, there are several different definitions of utility in wireless communication systems. The work presented in [11] compared and analyzed several definitions. It has been widely accepted that the utility function suggested in [5] and [12] is reasonable. In this definition, a user's utility is expressed as

$$u(p) = \frac{T(p)}{p} \quad \text{bits/joule.} \tag{2}$$

Here, utility $u(p)$ is proportional to throughput $T(p)$ and inversely proportional to power p. The utility is interpreted as the number of information bits received per joule of energy consumed. Specifically, we want to see that as $p \to \infty$, we have $u(p) \to 0$, and as $p \to 0$, we have $u(p) \to 0$. This simply reinforces the intuition that tells us that no desirable result will be obtained if we transmit at a power of either 0 or infinite.

The throughput $T(p)$ is interpreted as the number of information bits successfully received per second. An assumption in this model is that the data bits are packed into frames of M bits containing $L < M$ information bits per frame, where $L-M$ bits are used for error detection. Assuming a busy source model, in which nodes always have data to send, the throughput can be expressed as

$$T(p) = \left(\frac{L}{M}\right) W f(\gamma) \tag{3}$$

where $f(\gamma)$ denotes the probability of correct reception of a frame, i.e.,

$$f(\gamma) = [1 - \mathrm{BER}(\gamma)]^M . \tag{4}$$

Here, $\gamma = hp/N_0W$ is the received signal-to-noise ratio (SNR), with h, W, and N_0 being the channel gain, signal bandwidth, and noise spectral density, respectively. $f(\gamma)$ is an increasing function of γ. BER(γ) is the binary error rate of the transmitter–receiver pair. A frame is assumed to be retransmitted until received correctly while deriving the above expression [12]. It is noted that when $p = 0$, the numerator of (4) is positive, and the function is infinite. Reference [12] utilized an approximation to solve this problem, in which

$$f(\gamma) = [1 - 2\mathrm{BER}(\gamma)]^M \tag{5}$$

was adopted to replace the original $f(\gamma)$, and it was demonstrated to be reasonable. We will use this formula in our study.

Now, let us analyze the utilities of the users in Fig. 1. Let us first look at user 1. If p_1 is user 1's transmit power, the utility of user 1 should be

$$U_1(p_1, m, n) = \frac{\left[T_{1a}^D(p_1, m, n) + T_{\mathrm{AF}}^{(1,2)}(p_1, m, n)\right]}{p_1} \tag{6}$$

which illustrates that user 1's throughput is constructed by two parts, i.e., direct transmission part and cooperative transmission part. The first term $T_{1a}^D(p_1, m, n)$ occupies $1 - m - n$ fraction of its bandwidth, and the second term $T_{\mathrm{AF}}^{(1,2)}(p_1, m, n)$ (the subscript AF indicates amplified and forward) occupies n fraction of both users' bandwidth. The remaining m fraction of user 1's bandwidth is used to relay user 2's data and should not be counted into user 1's throughput.

For simplicity, we choose to keep p_i/W, $i = 1, 2$, i.e., the value of power per unit bandwidth, to be constant for the channels from the ith user to the AP as well as the channels between users, regardless of the way of bandwidth partitioning. Therefore, the SNRs on the channels are independent of the bandwidth partitioning as well. Under this assumption, the direct transmission throughput from user 1 to AP is

$$T_{1a}^D(p_1, m, n) = \left(\frac{L}{M}\right) W f(\gamma_{1a})(1 - m - n) \tag{7}$$

and the cooperative transmission throughput with relaying of user 2 is

$$T_{\mathrm{AF}}^{(1,2)}(p_1, m, n) = \left(\frac{L}{M}\right) W f\left(\gamma_{AF}^{(1,2)}\right) n \tag{8}$$

where

$$\gamma_{AF}^{(1,2)} = \gamma_{1a} + \frac{\gamma_{12}\gamma_{2a}}{1 + \gamma_{12} + \gamma_{2a}} \tag{9}$$

is the effective SNR of the AF cooperative channel from user 1 to AP. γ_{1a}, γ_{2a}, and γ_{12} are the SNRs of the wireless channels from user 1 to AP, from user 2 to AP, and from user 1 to user 2, respectively. Combining (6)–(8), we obtain user 1's utility function as

$$U_1(p_1, m, n) = \frac{LW}{Mp_1}\left[f(\gamma_{1a})(1 - m - n) + f\left(\gamma_{AF}^{(1,2)}\right) n\right]$$
$$m \geq 0, \quad n \geq 0, \quad m + n \leq 1. \tag{10}$$

Since the model is completely symmetric, the analysis is the same for user 2. We directly present user 2's utility as

$$U_2(p_2, m, n) = \frac{LW}{Mp_2}\left[f(\gamma_{2a})(1 - m - n) + f\left(\gamma_{AF}^{(2,1)}\right) m\right]$$
$$m \geq 0, \quad n \geq 0, \quad m + n \leq 1 \tag{11}$$

where

$$\gamma_{AF}^{(2,1)} = \gamma_{2a} + \frac{\gamma_{21}\gamma_{1a}}{1 + \gamma_{21} + \gamma_{1a}} \tag{12}$$

is the effective SNR of the AF cooperative channel from user 2 to AP, and γ_{21} is the received SNR of the wireless channel from user 2 to user 1.

IV. Cooperative Strategy Based on NBS

In this section, we will make use of the cooperative game theory to analyze the system defined in the previous section. First, we will prove that the interplay between the users in our proposed system can be modeled as a two-person bargaining problem. Then, a cooperation bandwidth allocation strategy based on NBS will be presented.

A. *Bargaining Problem*

The bargaining problem of the cooperative game theory can be described as follows [13]. Let $k = 1, 2, \ldots, K$ be the set of players, and S be a closed and convex subset of $\Re^K$ to represent the set of feasible payoff allocations that the players can get if they all work together. Let $\bar{U}_i$ be the minimal payoff that the ith player would expect. The pair $(S, \bar{U}_i)$ is called a K-person bargaining problem. Given the transmit power, we can prove that our problem is a two-person bargaining problem.

First, we use S_i to represent the set of feasible payoff allocations for user i, i.e.,

$$S_i = \{U_i | U_i = U_i(p_i, m, n),\ m \geq 0, n \geq 0, m + n \leq 1\}. \tag{13}$$

Then, the set of feasible payoff allocations that the two players can get when they work together is

$$S = \{U = (U_1, U_2) | U_1 \in S_1, U_2 \in S_2\}. \tag{14}$$

From the definition of the bargaining problem, we know that S should be a closed and convex subset of $\Re^2$. Since it is obvious that S is closed, we only need to prove that S is convex, which means for any $0 \leq \theta \leq 1$, if $U^a = (U_1^a, U_2^a) \in S$ and $U^b = (U_1^b, U_2^b) \in S$, $\theta U^a + (1 - \theta)U^b \in S$.

By simple derivation, we can get

$$\theta U_1^a + (1-\theta)U_1^b = \frac{LW}{Mp_1}\left[f(\gamma_{1a})(1-\alpha-\beta) + f\left(\gamma_{AF}^{(1,2)}\right)\beta\right] \tag{15}$$

where $\alpha = \theta m^a + (1 - \theta)m^b$, and $\beta = \theta n^a - (1 - \theta)n^b$. Because $m^a, m^b, n^a, n^b \geq 0$, $m^a + n^a \leq 1$, $m^b + n^b \leq 1$, and $0 \leq \theta \leq 1$, it is easy to derive

$$\alpha \geq 0, \quad \beta \geq 0, \quad \alpha + \beta \leq 1. \tag{16}$$

Thus, $\theta U_1^a + (1-\theta)U_1^b \in S_1$. We can also prove by the same method that $\theta U_2^a + (1-\theta)U_2^b \in S_2$. Therefore, $\theta U^a + (1-\theta)U^b \in S$, and S is convex. This way, we have proved that the game between users in our system is indeed a two-person bargaining problem.

B. NBS

In cooperative game theory, when analyzing the K-person bargaining problem, the cooperative solution should satisfy four axioms, i.e., invariance, efficiency, independence of irrelevant alternatives, and symmetry. In detail, for a two-person game, assuming that the cooperative solution is $U^* = (U_1^*, U_2^*)$ (U^* is the function of S and $\bar{U} = (\bar{U}_1, \bar{U}_2)$ which is the quitting cooperation point), the meaning of those axioms is explained as follows.

1) *Invariance:* For any monotone incremental linear function F, we always have

$$U^*\left[F(\bar{U}), F(S)\right] = F\left[U^*(\bar{U}, S)\right]. \tag{17}$$

2) *Efficiency:* The cooperative solution is Pareto-optimal, which means that it is impossible to improve both players' utilities at the same time. The mathematical expression is

$$(U_1, U_2) > U^* \Rightarrow (U_1, U_2) \notin S. \tag{18}$$

3) *Independence of Irrelevant Alternatives:* Take out some utility combinations from S, and get a smaller set S'. If U^* is not taken from S, U^* will not be changed, or

$$U^*(\bar{U}, S) \in S' \subseteq S \Rightarrow U^*(\bar{U}, S') = U^*(\bar{U}, S). \tag{19}$$

4) *Symmetry:* Exchanging the positions of those two players does not affect the cooperative solution.

C. Existence and Uniqueness of NBS

Nash proved that there is a unique solution function for a K-person bargaining problem that satisfies all the four axioms. This solution satisfies [13]

$$U^* = \underset{U_i > \bar{U}_i}{\operatorname{Arg\,max}} \prod_{i=1}^{K} (U_i - \bar{U}_i) \tag{20}$$

which is the well-known NBS.

For the two-person bargaining problem presented above, the NBS function should be expressed as

$$U^* = \underset{U_i(p_i,m,n) > \bar{U}_i}{\operatorname{Arg\,max}} \left[U_1(p_1,m,n) - \bar{U}_1\right]\left[U_2(p_2,m,n) - \bar{U}_2\right] \tag{21}$$

which is subjected to (1). Here, $\bar{U}_1 = (LW/Mp_1)f(\gamma_{1a})$ and $\bar{U}_2 = (LW/Mp_2)f(\gamma_{2a})$ represent the utility of user 1 and user 2 in case of noncooperation, respectively. User i will quit cooperation when its utility cannot achieve $\bar{U}_i$, which ensures user i's utility to be no less than $\bar{U}_i$. A conclusion could be drawn from the above NBS function that the users would participate cooperation only if their performance is better than that of direct transmission.

D. Cooperation Bandwidth Allocation Strategy

Next, we will derive the cooperation bandwidth (m and n) that satisfies the NBS function. For the sake of simplicity, U_i is utilized to replace $U_i(p_i, m, n)$ in the rest of this paper. Since

$$U_1 - \bar{U}_1 = \frac{LW}{Mp_1}\left\{\left[f\left(\gamma_{AF}^{(1,2)}\right) - f(\gamma_{1a})\right]n - f(\gamma_{1a})m\right\} \tag{22}$$

$$U_2 - \bar{U}_2 = \frac{LW}{Mp_2}\left\{\left[f\left(\gamma_{AF}^{(2,1)}\right) - f(\gamma_{2a})\right]m - f(\gamma_{2a})n\right\} \tag{23}$$

if we let $A = f(\gamma_{AF}^{(1,2)}) - f(\gamma_{1a})$, $E = f(\gamma_{1a})$, $B = f(\gamma_{AF}^{(2,1)}) - f(\gamma_{2a})$, and $F = f(\gamma_{2a})$, we have

$$(U_1 - \bar{U}_1)(U_2 - \bar{U}_2) = \left(\frac{LW}{M}\right)^2 \times \frac{1}{p_1 p_2}(An - Em)(Bm - Fn). \tag{24}$$

Let $An - Em = X$ and $Bm - Fn = Y$. The NBS function turns into the form

$$(U_1 - \bar{U}_1)(U_2 - \bar{U}_2) = \left(\frac{LW}{M}\right)^2 \frac{1}{p_1 p_2} XY. \tag{25}$$

Given the users' transmit power, because the parameter $(LW/M)^2(1/p_1p_2)$ is constant, our problem is to find the optimal parameters m and n that maximize the product XY. The relations between m, n and X, Y are given as

$$\begin{cases} m = \frac{1}{AB-EF}(AY + FX) \\ n = \frac{1}{AB-EF}(BX + EY). \end{cases} \tag{26}$$

If $AB > EF$, the restrictions given in (1) is equivalent to

$$\begin{cases} AY + FX \geq 0 \\ EY + BX \geq 0 \\ (A+E)Y + (B+F)X \leq AB - EF. \end{cases} \tag{27}$$

As depicted in Fig. 2, the triangle represents the points of (X, Y) satisfying the restriction given in (27), and we need to find out the point that maximizes the product XY. Obviously, the point should be located on line $(A+E)Y + (B+F)X = AB - EF$ such that $\max(XY) = \max(-((B+F)/(A+E))X^2 + (AB - EF/A + E)X)$. It is easy to derive that when

$$(X, Y) = \left(\frac{AB - EF}{2(B+F)}, \frac{AB - EF}{2(A+E)}\right) \tag{28}$$

XY is maximized, and the cooperation bandwidths are

$$\begin{cases} m = \frac{A}{2(A+E)} + \frac{F}{2(B+F)} \\ n = \frac{E}{2(A+E)} + \frac{B}{2(B+F)}. \end{cases} \tag{29}$$

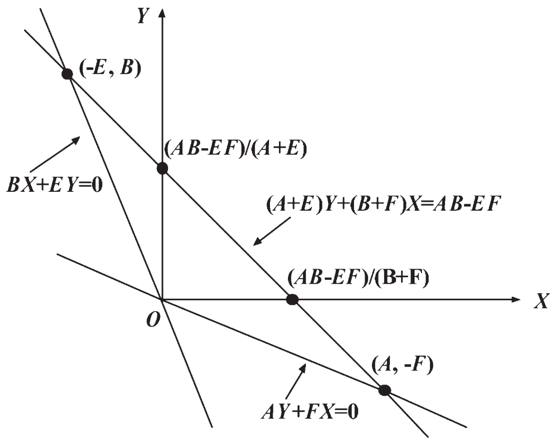

Fig. 2. (X, Y) restricted within a triangle when $AB > EF$.

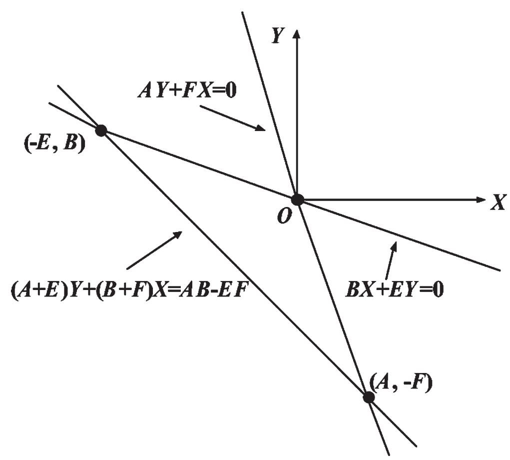

Fig. 3. (X, Y) restricted within a triangle when $AB \leq EF$.

Inserting the expressions of A, B, E, and F into the above equation, we get

$$\begin{cases} m = \frac{1}{2}\left(1 - \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} + \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)}\right) \\ n = \frac{1}{2}\left(1 + \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} - \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)}\right). \end{cases} \tag{30}$$

If $AB \leq EF$, the restriction (1) is equivalent to

$$\begin{cases} AY + FX \leq 0 \\ EY + BX \leq 0 \\ (A+E)Y + (B+F)X \geq AB - EF. \end{cases} \tag{31}$$

As illustrated in Fig. 3, the triangle represents the points of (X, Y) satisfying the restriction (31). Note that the maximization in (21) takes over all the utilities greater than those of the noncooperation case, which means both X and Y should be greater than 0; otherwise, the users will choose not to cooperate. Therefore, the point that maximizes XY could only be located on line $AY + FX = 0$ or line $EY + BX = 0$. It results in the optimal $(X, Y) = (0, 0)$, and the corresponding cooperation bandwidth parameters turn out to be $m = 0$, $n = 0$, which indicates that users do not cooperate at all. Substituted by the original variables, the expression $AB > EF$ can be rewritten as $f(\gamma_{AF}^{(1,2)})f(\gamma_{AF}^{(2,1)}) - f(\gamma_{AF}^{(1,2)})f(\gamma_{2a}) - f(\gamma_{AF}^{(2,1)})f(\gamma_{1a}) > 0$. Then, we get the following theorem.

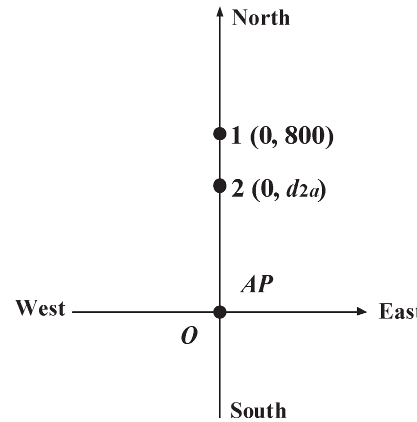

Fig. 4. Locations of two users and AP considered in the simulations.

Theorem 1: Given the users' transmit power, if $f(\gamma_{AF}^{(1,2)})f(\gamma_{AF}^{(2,1)}) - f(\gamma_{AF}^{(1,2)})f(\gamma_{2a}) - f(\gamma_{AF}^{(2,1)})f(\gamma_{1a}) > 0$, the cooperation bandwidths of the two users become

$$\begin{cases} m = \frac{1}{2}\left(1 - \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} + \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)}\right) \\ n = \frac{1}{2}\left(1 + \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} - \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)}\right). \end{cases} \tag{32}$$

Otherwise, the users do not cooperate.

Note that at the edge of the condition boundary, i.e., when $f(\gamma_{AF}^{(1,2)})f(\gamma_{AF}^{(2,1)}) - f(\gamma_{AF}^{(1,2)})f(\gamma_{2a}) - f(\gamma_{AF}^{(2,1)})f(\gamma_{1a}) = 0$, or, equivalently, $1 - (f(\gamma_{1a})/f(\gamma_{AF}^{(1,2)})) - (f(\gamma_{2a})/f(\gamma_{AF}^{(2,1)})) = 0$, it yields

$$\begin{cases} m = \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)} = 1 - \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} \\ n = \frac{f(\gamma_{1a})}{f\left(\gamma_{AF}^{(1,2)}\right)} = 1 - \frac{f(\gamma_{2a})}{f\left(\gamma_{AF}^{(2,1)}\right)}. \end{cases} \tag{33}$$

Obviously, there is $m, n > 0$ and $m + n = 1$ at this time, which means that, when the system is experiencing across the condition boundary, there must be a sudden change in the amount of m and n, i.e., from 0 to a certain positive value determined by the above equations. To explain this, we recall that only if both $U_1 \geq \bar{U}_1$ and $U_2 \geq \bar{U}_2$ are held will the users choose to cooperate. Substituting (33) into (22) and (23), it just results in $U_1 = \bar{U}_1$ and $U_2 = \bar{U}_2$. In other words, the above (m, n) is just a start point for users to cooperate.

V. Simulation Results

As illustrated in Fig. 4, we consider a network in which an AP is located at the origin and user 1 is situated 800 m north of the AP such that the coordinates of user 1 are (0, 800). User 2 is moving along the Y-axis, and thus, the coordinates of user 2 are (0, d_{2a}). We observe the cooperation behavior at different locations of user 2. The other parameters used in the simulations include $L = 64$, $M = 80$, $\text{BER}(\gamma) = (1/2)\exp(-\gamma/2)$ for noncoherent frequency shift keyed, $W = 10^6$ Hz (bandwidth), and $N_0 W \equiv 5 \times 10^{-15}$ W (noise variance). We have also used a path gain formula given by $h = (7.75 \times 10^{-3})/d^{3.6}$ [12], where d is the distance between the transmitter and the receiver (in meters). The transmit power is assumed to be 0.1 W for both users.

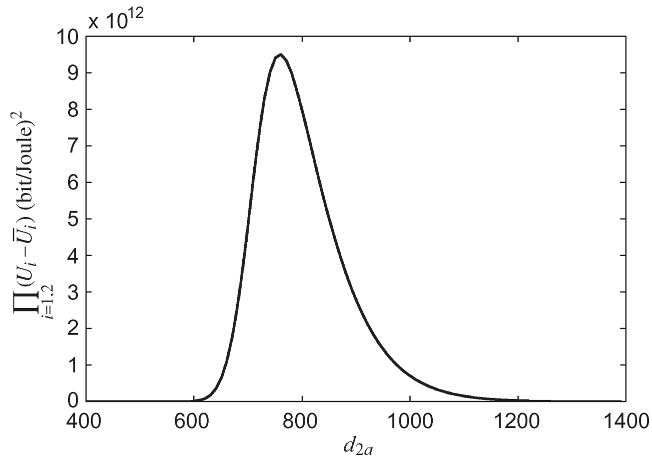

Fig. 5. Value of $(U_1 - \bar{U}_1)(U_2 - \bar{U}_2)$ versus different locations of user 2.

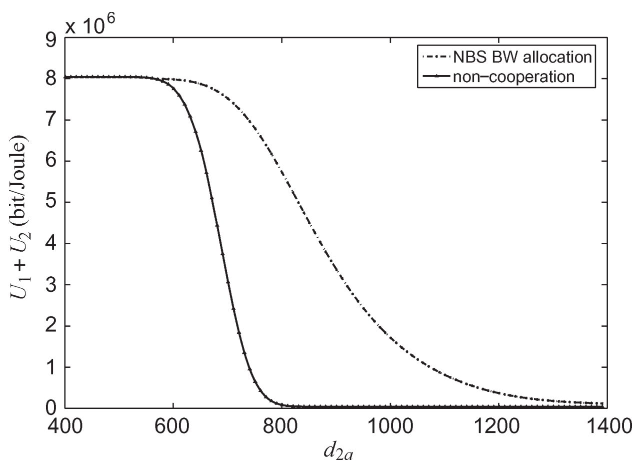

Fig. 6. Sum utility of the cooperative system with the proposed cooperative bandwidth allocation strategy versus the fixed noncooperative strategy.

In Fig. 5, the Y-axis represents $\prod_{i=1,2}(U_i - \bar{U}_i)$, and the X-axis represents d_{2a}. When users do not cooperate, $\prod_{i=1,2}(U_i - \bar{U}_i)$ is always equal to 0, since user i's utility will always be $\bar{U}_i$. Looking at the X-axis, with the movement of user 2 from the left (near AP) to the right (far from AP), while $d_{2a} < 600$ (actually it should be $d_{2a} < 560$; however, from this figure we can only tell a rough number, and the cooperation bound is clearer in Fig. 7), we have $\prod_{i=1,2}(U_i - \bar{U}_i) = 0$, which indicates that users will adopt direct transmissions when user 2 is located in this region. However, in the region between 600 and 1200, $\prod_{i=1,2}(U_i - \bar{U}_i)$ becomes positive, which means that the cooperation between users brings each user an advantage in terms of utility. When $d_{2a} > 1200$, $\prod_{i=1,2}(U_i - \bar{U}_i)$ is almost 0. In fact, it is hard to tell from this figure whether users will cooperate or not within this region, and we will discuss this problem in the following figures.

Fig. 6 shows the system sum utility of the proposed cooperation bandwidth allocation strategy, as well as the fixed noncooperation strategy. The dashed line indicates the result of the proposed strategy, whereas the solid line denotes the result of the fixed noncooperation strategy. We can observe that when d_{2a} is small, those two strategies have the same performance, which indicates that direct transmission is dominant, and, thus, our strategy makes users independently work. In the middle

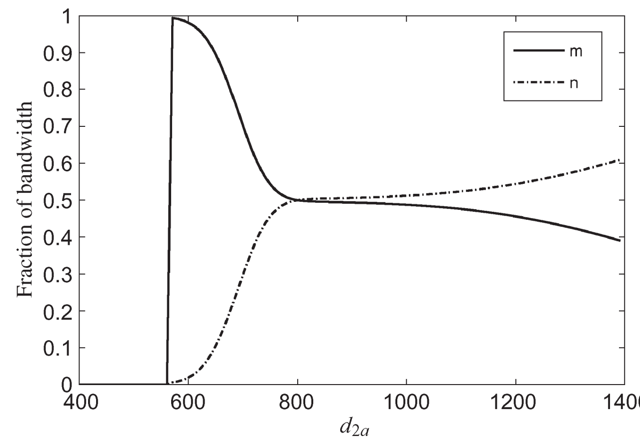

Fig. 7. Fraction of cooperation bandwidth versus different location of user 2.

area, the proposed strategy makes the users cooperatively work, and the cooperation substantially improves the sum utility of the entire system. However, this advantage becomes diminished when $d_{2a} > 1200$, which indicates that although cooperation can improve the sum utility, the improvement is trivial in this case.

Fig. 7 shows the cooperation bandwidth allocation results of the proposed strategy. When $d_{2a} < 560$, $m = n = 0$, and, thus, no user is willing to relay the data of the other. Users start cooperation since $d_{2a} = 560$. The relation of cooperation bandwidth is $m > n$, when $d_{2a} < 800$, because user 2's channel condition is better than user 1's within this region, and thus, user 1 is willing to take out more bandwidth for cooperation to exchange for user 2's relaying. When $d_{2a} > 800$, the situation reverses. With the increase of d_{2a}, user 2's channel condition becomes worse, and more bandwidth is required for cooperation. An extreme case is that when user 2 is very far from AP, this user needs to contribute all its bandwidth for relaying. However, no matter whose data user 2 transmits, the BER at the AP has the same value of about 0.5, and user 1, of course, will save all the resources for its own transmission. Thus, in this extreme case, although user 2 is cooperative, the result is equivalent to noncooperation. As shown in the figure, there is a sudden change in the value of m and n when user 2 moves across the cooperation start point $d_{2a} = 560$. As discussed right after Theorem 1, when the users start to cooperate, the value of m and n will change from 0 to a certain positive one that is determined by (33) to ensure the utilities of both users will not decrease. Here, the change of m looks much larger than that of n, and the latter is almost invisible, which is only the result of a relatively small $f(\gamma_{1a})/f(\gamma_{AF}^{(1,2)})$ in the studied case.

Fig. 8 illustrates the user utility of the proposed strategy as well as the fixed noncooperative strategy. The logarithmic coordinate is adopted in the Y-axis. When d_{2a} is small, users do not cooperate at all, and thus, user 1's utility of both strategies remains unchanged. Although user 2's channel varies when it moves, $f(\gamma_2) \approx 1$, and user 2's utility of both strategies only slightly changes because of the good channel condition. Whereas $d_{2a} > 560$, the users' utilities of the proposed strategy are improved in comparison with the noncooperative strategy, which demonstrates that our proposal can enhance system performance by proper cooperation.

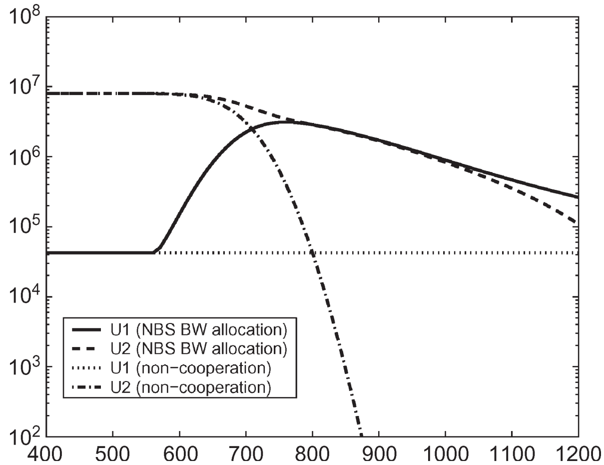

Fig. 8. User utilities with the proposed strategy, where the logarithmic coordinate is adopted on the Y-axis.

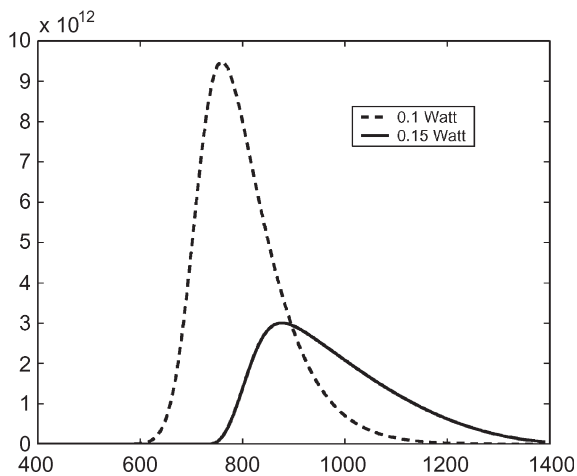

Fig. 9. Value of $(U_1 - \bar{U}_1)(U_2 - \bar{U}_2)$ versus different locations of user 2 with different transmit power.

In all of the above simulations, it is assumed that the transmit power of both users is fixed at 0.1 W. Indeed, the transmit power affects the utilities of users quite a lot. Fig. 9 shows the $(U_1 - \bar{U}_1)(U_2 - \bar{U}_2)$ performance with different transmit powers. When the transmit power is 0.15 W, cooperation happens when $d_{2a} > 750$, which is different from the 0.1-W case.

VI. Discussions

A. Power Control

In the above analysis, we have assumed that the user's transmit power is fixed. However, if power control is involved in the cooperative system, the problem becomes very complex because it may no longer be convex. To jointly find the optimal value of transmit power and the cooperation bandwidth is a very difficult task. One possible way is to search for the best value in the range of the two users' power constraints with an appropriate searching step. For each transmit power pair, the optimal cooperation bandwidth is able to be found by the strategy proposed above, and so is the corresponding $(U_1 - \bar{U}_1)(U_2 - \bar{U}_2)$. Adjusting the users' transmit power values until the maximum of $(U_1 - \bar{U}_1)(U_2 - \bar{U}_2)$ is found, we take these values of power and bandwidth fraction as the optimal parameters.

This approach is based only on a heuristic method. The performance and complexity may be greatly influenced by the searching step. How to effectively search for the optimal transmit power and cooperation bandwidth is interesting work, which we will leave for future research.

B. Network Implementation

Obviously, the proposed strategy can also be readily applied to cellular networks, where the base station resembles the AP and computes cooperation bandwidths and informs mobiles about the results through signaling channels. On the other hand, in distributed *ad hoc* networks, where there is no central controller, as long as the channel gains for each transmitter–receiver pair in a three-node subsystem are accessible to both users, our proposed strategy will still be able to work in a distributed manner. The cooperation bandwidths should be independently computed by users 1 and 2 by utilizing the same algorithm.

In a large network where there are more than two users, a router is supposed to exist in the network, and it can divide users into pairs based on their geographical locations, e.g., grouping the close-by users into pairs and letting each pair communicate with the nearest AP. If there are odd numbers of users in the network, one user will be left out, and it has to work independently. Then, each user pair together with the AP will build up a subsystem to work cooperatively, just like we have discussed above. Our proposed strategy can be readily used in the subsystem. Here, we only present a simple and heuristic description of the user partitioning problem, and a lot of implementation issues are left open, which may be very complex depending on the network scale, routing algorithms, etc. This can be another interesting topic in our future research.

VII. Conclusion

In this paper, we have analyzed the cooperative behavior of rational nodes in a wireless network. First, a symmetric system model comprising two users and an AP is presented, where each user acts as a source as well as a potential relay in the system and decides the bandwidth it can use for cooperation. Then, we proved that this issue can be effectively modeled by a two-person bargaining problem. With the help of cooperative game theory, a cooperation bandwidth allocation strategy based on NBS is proposed. Our strategy can solve the problem of when to cooperate (cooperation condition) and how to cooperate (cooperation bandwidth). The simulation results show that users benefit from the proposed strategy in terms of utility, and the user with longer distance from AP should take more bandwidth for cooperation when cooperation takes place. As an extreme, when a user is infinitely far away from the AP, it has to utilize all its bandwidth to cooperate, having the same result with that of no cooperation at all, since the other node will not waste its resource to sacrifice its own utility. In addition, we also discussed some related issues when putting the proposed strategy into real application, such as power control and large-scale network implementation.

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