Joint resource allocation based on Nash bargaining game for wireless cooperative networks

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Abstract

This paper considers the problem of resource sharing among selfish nodes in wireless cooperative networks. In the system, each node can be acted as a source as well as a potential relay, and both nodes are willing to achieve an extra rate increase by jointly adjusting their channel bandwidth and power levels for cooperative relaying. Nash bargaining solution (NBS) is applied to formulate the JBPA problem to guarantee fairness. Simulation results indicate the NBS resource sharing is fair and the fairness of resource allocation only depends on how much contribution its partner can make to its rate increase.

Keywords: Nash bargaining solution, bandwidth allocation, power control

1 Introduction

Cooperative diversity has been proposed for wireless network applications to enhance system coverage, link reliability and data transmission, and to decrease bit error rate (BER) [1] in recent years. Generally, all nodes in a non-commercial wireless network are assumed cooperative. In our daily life, the market often serves as a central platform where buyers and sellers gather together, negotiate transactions and exchange goods so that they can be satisfied immediately through bargaining and buying or selling. Similarly, the cooperation game theory just provides a flexible and natural tool to explore how the selfish nodes bargain with each other and mutual aid.

The pioneering work can be found in the following references. In [2], based on the NBS, the authors proposed a novel two-tier quality of service (QoS) framework and a scheduling scheme for QoS provisioning in worldwide interoperability for microwave access networks. A resource allocating scheme based on the NBS for downlink orthogonal frequency-division multiple access (OFDMA) wireless networks was proposed in [3]. The authors in [4] proposed a cooperation bandwidth allocation strategy for the throughput per unit power increase. In [5] the authors considered a bandwidth exchange incentive mechanism as a means of providing incentive for forwarding data. However, only bandwidth allocation problem was considered to encourage cooperation in [3-5]. In [6-8] the power allocation problem was considered to encourage cooperation. The authors in [6] considered fair power sharing between a user and its partner for an optimal signal-to-noise ratio (SNR) increase. From an energy-efficiency, perspective based no NBS, the authors in [7] studied a cellular framework including two mobile users desiring to communicate with a common base station. In order to obtain both user fairness and network efficiency, a cooperative power-control game model based on Nash bargaining was formulated in [8]. In order to improve the fairness of virtual bandwidth allocation for multi tenants, especially for virtual links, the authors in [9] proposed a utility-maximization model for bandwidth sharing between virtual networks in the same substrate network.

However, the bandwidth only or power only allocation problem was studied in previous work, ignoring the JBPA in wireless network communication. Motivated by the aforementioned works, we constructed a symmetric wireless system model consisting of two user nodes and two destination nodes, which is shown in Figure 1.

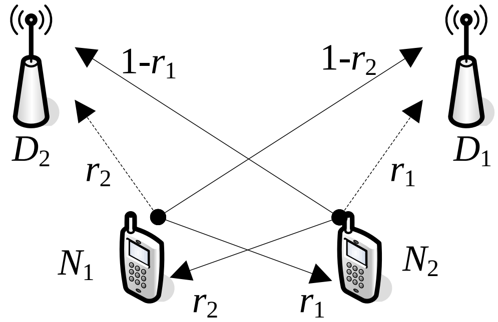

FIGURE 1 The system model for cooperative transmission

In the model, it is assumed that each user acts as a source as well as a potential relay. Furthermore, the proposed model represents a more general scenario, comparing to previous work. By bandwidth and power exchanging, each user has the opportunity to share the other's resources (e.g., bandwidth and power) and seek other user's help to relay its data to obtain the cooperative diversity, and vice versa. The cooperation degree between

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partners depends on two factors: one is the bandwidth and power contribution of each node on the cooperative rate increment; and another is their channel condition of each node on its cooperation benefit in terms of cooperative rate increment.

2 System model and cooperative schemes

As is shown in Figure 1, there is a symmetric cooperative communication system model [1] consists of two source nodes, N_1 and N_2, and their corresponding destination nodes, D_1 and D_2 (in particular, D_1=D_2). The two cooperating nodes communicate independent information over the orthogonal channels to the destinations.

The AF cooperation protocol is used in the model. The AF cooperative transmission between the two nodes occurs in two time slots. The system model is based on frequency division multiple access and each user occupies W hertz bandwidth for transmission. The total power consumptions of each user in the two time slots are the same.

As illustrated in Figure 2, N_1 and N_2 work independently to transmit their own data to D_1 and D_2 at time slot 1 with power P_1 and time slot 2 with power P_2 respectively. However, each user may seek other user's cooperation to relay its data to obtain the cooperative diversity. As shown in Figure 3, in time slot 1, N_1 transmits its own data independently with a part of its power, sharing a part of the common bandwidth, and N_1 simultaneously relays the data originating from node N_2 with another part of its power and another part of the common bandwidth. And vice versa for N_2 in the next time slot.

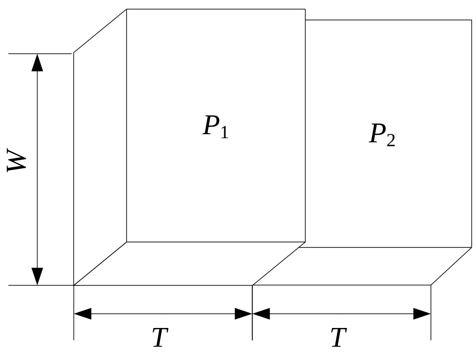

FIGURE 2 Direct transmission with interference

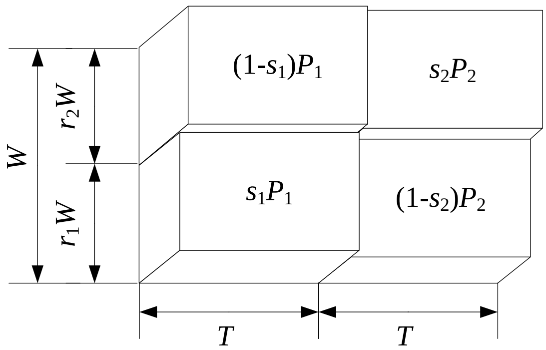

FIGURE 3 Time-division and frequency-division channel for JBPA

The details of cooperation between two nodes are illustrated in Figure 3. Specifically, in time slot 1, node N_1 allocates r_2 fraction ($r_2 \in (0, 1)$) of its bandwidth and 1-s_1 fraction ($s_1 \in (0, 1)$) of its power P_1 to relay r_2 fraction of the data from node N_2, and it uses the r_1 fraction ($r_1 \in (0, 1)$) of the bandwidth and s_1 fraction ($s_1 \in (0, 1)$) of its power for its own data transmission. In time slot 2, node N_2 uses r_1 fraction ($r_1 \in (0,1)$) of the bandwidth and 1-s_2 fraction ($s_2 \in (0, 1)$) of its power P_2 to forward the data originating from node N_1, and it uses the r_2 fraction of the bandwidth and s_2 fraction of its power for its own data transmission.

According to the cooperation details described above, a relay can forward no more than the amount of data as that originating from the source itself. There is r_1=1-r_2, which came from the result of [4]. Obviously, both r_1 and r_2 should be nonnegative for a meaningful cooperation. Then, we have

$$r_1 + r_2 = 1,\ r_1 > 0,\ r_2 > 0\ . \tag{1}$$

Suppose that subscript denotes source node and superscript denotes destination node. Let G_i^j represents the channel gain between node N_i and node D_j ($i \neq j$), and let G_{ij} denote the channel gain from node N_i to node N_j. We assume that the noise power spectral density at different receivers is i.i.d. with the N_0. The cooperative transmission consists of two phases. In time slot 1, assumed that x_1 is the broadcasted signal from N_1 to N_2 and destination D_1, then, the achieved SNR helped by N_2 for N_1 to D_1 is given by [1]

$$\gamma_{12}^1 = \frac{s_1(1-s_2)P_2G_2^1P_1G_{12}}{\sigma_1^2\left[(1-s_1)P_2G_2^1 + s_1P_1G_{12} + \sigma_1^2\right]}\ . \tag{2}$$

And the effective rate of node N_1 at the D_1 is

$$r_1R_{12}^{AF} = r_1W\log\left(1+\gamma_1^1+\gamma_{12}^1\right) \tag{3}$$

where $\sigma_1^2 = r_1WN_0$ and $\gamma_1^1 = s_1P_1G_1^1/\sigma_1^2$ is the SNR that results from the direct transmission from node N_1 to the D_1 in the first time slot.

Similarly, the relayed SNR helped by N_1 for N_2 to D_2 is given by [1]

$$\gamma_{21}^2 = \frac{s_2(1-s_1)P_1G_1^2P_2G_{12}}{\sigma_2^2\left[(1-s_1)P_1G_1^2 + s_2P_2G_{12} + \sigma_2^2\right]}\ . \tag{4}$$

The effective rate of node N_2 at the D_2 is

$$r_2R_{21}^{AF} = r_2W\log\left(1+\gamma_2^2+\gamma_{21}^2\right) \tag{5}$$

where $\sigma_2^2 = r_2WN_0$ and $\gamma_2^2 = s_2P_2G_2^2/\sigma_2^2$ is the SNR that results from the direct transmission from node N_2 to the D_2 in the first time slot.

However, N_1 and N_2 may prefer working independently to transmit their own data, if it could make up the opportunity cost of cooperative transmission by direct transmission. As illustrated in Figure 2. Then the direct rate at the D_1 is $R_1^D = W\log\left(1+P_1G_1^1/\sigma_0^2\right)$, and the direct rate at the D_2 is $R_2^D = W\log\left(1+P_2G_2^2/\sigma_0^2\right)$, where σ_0^2 is the AWGN received at the destination D_1 and D_2 on the condition of no partner for cooperation.

From the above introduction, it's clear that the resource allocation variables r_2 and s_1 reflect the N_1's rational decisions while r_1 and s_2 reflect the decisions of N_2, i.e., N_1 determines r_2 and N_2 determines r_1, and that the decisions of one user will affect the choices of its partner. Their pay out and payoff should be traded off and both users expect an optimal trade-off. The following sections will focus on in particular this problem's solution that can bring about win-win results.

3 Utility function and problem formulation

In this section, the utility functions of the source nodes are given and the model is analysed via the cooperative game theory. For node N_1 and node N_2, their utility functions U_1 and U_2 can be defined as $U_1 = r_1R_{12}^{AF}$ and $U_2 = r_2R_{21}^{AF}$, respectively. It is obvious that node N_1 will quit cooperation when its payoff is less than R_1^D, which ensures that a node would participate in cooperative transmission only if its effective rate is better than that of direct transmission. So the minimal values of U_1 and U_2 must be $U_1^{\min} = R_1^D$ and $U_2^{\min} = R_2^D$, respectively.

The bargaining problem of cooperative game theory can be described as follows. Let K={1,2} be the set of players. Let S be a closed and convex subset of R^K to represent the set of feasible payoff allocations that the players can get if they all work together. Let U_k^{min} be the minimal payoff that the k-th player would expect; otherwise, it will not cooperate. Suppose $\left\{U_k \in S \mid U_k > U_k^{\min}, \forall k \in K\right\}$ is a nonempty bounded set. Define $U^{min}=(U_1^{min}, U_2^{min})$, then the pair ($S$, U^{min}) is called a two-person bargaining problem.

As discussed above, each user has U_i as its objective function, where is bounded above and has a nonempty, closed, and convex support. The goal is to maximize all U_i simultaneously. U^{min} represents the minimal performance, and U^{min} is called the initial agreement point. The problem, then, is to find a simple way to choose the operating point in S for all users, such that this point is optimal and fair.

4 Joint resource allocation algorithm

Now, observe that the close form solution of (20) is impossibly to be got. So, we develop a numerical search algorithm, by which a global maximum not a local maximum will be obtained.

According to decomposition optimization theory [10], the optimization problem can be equivalently decomposed into the following two problems. Firstly, the maximal bandwidth solve

$$\tilde{U}^*(\tilde{r}_1*, \tilde{r}_2*, s_1, s_2) = \underset{r_1, r_2 \in (0,1), r_1+r_2=1}{Arg\max}\ U(r_1, r_2, s_1, s_2), \forall s_1, s_2 \in (0,1), \quad (6)$$

where $\tilde{U}^*(\tilde{r}_1*, \tilde{r}_2*, s_1, s_2)$ is the maximal solution for given s_1 and s_2, not the optimal solution. $\tilde{r}_1*$ and $\tilde{r}_2*$ are the corresponding bandwidth allocation ratios.

Secondly, the optimal power allocation ratios solve

$$U^*(r_1*, r_2*, s_1*, s_2*) = \underset{s_1, s_2 \in (0,1)}{Arg\max}\ \tilde{U}^*(\tilde{r}_1*, \tilde{r}_2*, s_1, s_2) \quad (7)$$

In this phase, we compare all $\tilde{U}^*(\tilde{r}_1*, \tilde{r}_2*, s_1, s_2)$ and choose the maximal one for all $\tilde{r}_1*$ and $\tilde{r}_2*$. This way, we can obtain the optimal solution.

In the following, Theorem 1 will be proved, which show that (6) and (7) all have a unique Nash equilibrium solution.

Theorem 1: For $\forall s_1, s_2 \in (0,1)$, the two-user bargaining game admits a unique Nash equilibrium solution r=(r_1, r_2). For $\forall r_1, r_2 \in (0,1)$, the two-user bargaining game admits a unique Nash equilibrium solution s=(s_1, s_2).

Proof: See Appendix A

For given s_1 and s_2, there exist the corresponding bandwidth allocation ratios $\tilde{r}_1*$ and $\tilde{r}_2*$. Substituting $\tilde{r}_1*$ and $\tilde{r}_2*$ into R_{12}^{AF} and R_{21}^{AF} respectively. This way, R_{12}^{AF} and R_{21}^{AF} will not include variables r_1 and r_2. So we have

$$\tilde{U}^*(\tilde{r}_1*, \tilde{r}_2*, s_1, s_2) = \underset{\substack{r_1, r_2 \in (0,1), r_1+r_2=1 \\ ,\forall s_1, s_2 \in (0,1)}}{Arg\max}\ \left(r_1R_{12}^{AF} - R_1^D\right)\left(r_2R_{21}^{AF} - R_2^D\right) \quad (8)$$

For problem (8), by taking the derivative to r_1 and r_2 respectively, and equating them to zero, we get

$$\tilde{r}_1* = I_1\left(\tilde{r}_1*, \tilde{r}_2*\right) = 0.5\left[1 + R_1^D\left(R_{12}^{AF}\right)^{-1} - R_2^D\left(R_{21}^{AF}\right)^{-1}\right], \quad (9)$$

$$\tilde{r}_2* = I_2\left(\tilde{r}_1*, \tilde{r}_2*\right) = 0.5\left[1 - R_1^D\left(R_{12}^{AF}\right)^{-1} + R_2^D\left(R_{21}^{AF}\right)^{-1}\right]. \quad (10)$$

It is obvious that $\tilde{r}_1* + \tilde{r}_2* = 1$, which means that there is one variable only between $\tilde{r}_1*$ and $\tilde{r}_2*$. So the iterations of the bandwidth allocation ratio updating can be expressed as follows

$$\tilde{r}_i(t+1) = I_i\left(\tilde{r}_i(t)\right), i=1, 2\ . \quad (11)$$

We show next the convergence of the iterations in (11) by proving that the bandwidth allocation ratio updating function $I_i\left(\tilde{r}_i(t)\right)$ is a standard function [11].

Definition 1. A function $I_i\left(\tilde{r}_i\right)$ is standard if for all $\tilde{r}_i$ >0, the following properties are satisfied [11]:

1. Positivity. $I_i\left(\tilde{r}_i\right)>0$;

2. Monotonicity. If $\tilde{r}_i > \tilde{r}_i'$, then $I_i\left(\tilde{r}_i\right) \geq I_i\left(\tilde{r}_i'\right)$;

3. Scalability. For all $\alpha > 1$, $\alpha I_i\left(\tilde{r}_i\right) > I_i\left(\alpha\tilde{r}_i\right)$.

Proposition 1. The function $I_i\left(\tilde{r}_i\right)$ is standard.

Proof. See Appendix B.

In [11], a proof has been given. Starting from any feasible initial bandwidth allocation ratios r_1 and r_2, the bandwidth allocation ratios produced after several iterations of the standard bandwidth allocation algorithm gradually converges to a unique fixed point.

The problem (7) is a combinatorial problem which involves two continuous variables, s_1 and s_2. The optimal power allocation ratio s_1* and s_2* can be acquired by using gradient descent method.

5 Simulation results

To evaluate the performance of the proposed scheme, in what follows, the simulation results for JBPA are to be shown. A two-source and two-destination simulated system is conducted. Assumed that both nodes have the same initial transmission power with $P1= P2= 0.1$W, continuous strategy spaces with $r_1, r_2, s_1, s_2 \in (0, 1)$ and channel bandwidth with $W=10^6$Hz. The path gain is set to $(7.75\times10^{-3})/d^{3.6}$, where d is the distance between the transmitter and the receiver (in meters). The noise level is 5×10^{-14}W. We locate the N_2 at (0, 800)，D_2 at (0, 0), and D_1 at (0, 1200), and fix the y coordinate of N_1 at 400 while increase its x coordinate from 0 to 500.

Let $X1$ denotes the x coordinate of node N_1. Figure 4 shows the NBS strategies, i.e., the optimal cooperation ratios (r_1, r_2, s_1, s_2) of both nodes when node N_1 moves. With the movement of N_1 from the (0,400) to (500,400), N_1's bandwidth allocation ratio is decreasing and that of N_2 is increasing correspondingly. The relation of cooperation bandwidth is $r_1>r_2$, because N_2's channel condition is better than N_1's within this region, and thus, N_1 is willing to take out more bandwidth for cooperation to exchange for N_2's relaying. However, N_1 and N_2 are consuming most own power for themselves and small part of power for its partner. In N_1's moving process, N_2 is increasing more power for itself than N_1, because N_2's channel condition is better than N_1's within this region, and thus, N_1 is willing to take out more power for cooperation to exchange for N_2's relaying.

Figure 5 shows the performance comparisons of the proposed JBPA approach with the DT scheme, BA scheme and PA scheme. As shown in the Figure 5, the optimal rate obtained by BPJA approach is always bigger than the rate of BA scheme and the optimal rate obtained by BA scheme or by PA scheme is bigger than the rate of DT scheme, if the cooperation condition is satisfied and occurred. A node will choose not to cooperate when it can not get any benefit in the game.

From Figures 4 and 5, it's concluded that the proposed JBPA scheme could optimize the system performance while keeping the NBS fairness. The NBS fairness is embodied by the fact that the cooperative rate of each node is fundamentally determined by its channel condition, and that the cooperative rate increment of each node depends on its bandwidth and power contribution to maintain the cooperative transmission.

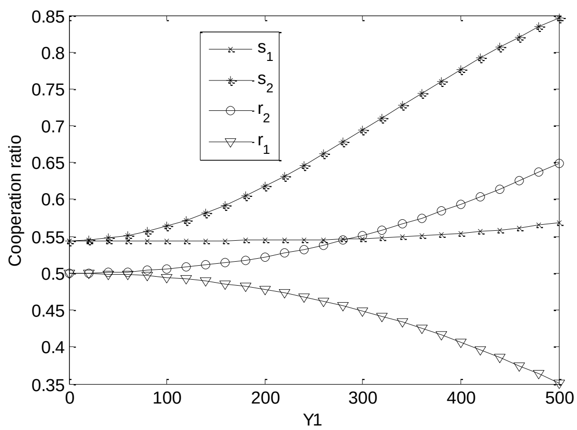

FIGURE 4 The optimal bandwidth and power cooperation ratios

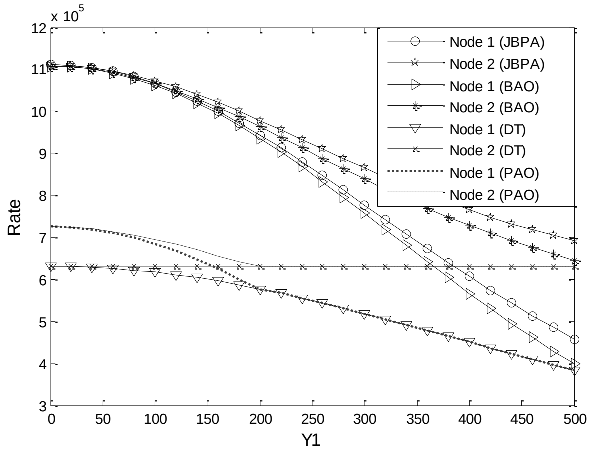

FIGURE 5 Three kinds of rates comparison

6 Conclusions

This paper has analysed the cooperation behaviour of selfish nodes in cooperative communication networks. We formulate the JBPA problem between two cooperating nodes as a cooperative game, and use the NBS function to obtain the solution of the game. Simulation results show that the resulting JBPA has the NBS fairness in that the degree of cooperation of a node only depends on how much contribution its partner can make to improve its performance. Furthermore, it is also shown that the proposed JBPA approach can achieve a comparable performance to that of the DT scheme, the BA scheme or PA scheme.

7 Acknowledgements

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8 Appendices

8.1 APPENDIX A: PROOF OF THEOREM 1

Observe that the constraint set is convex. So if $U_i(r_i)$ is proved to be concave for r_i, Theorem 1 will be proved. For simplified representation, we define

$$A_i = 1 + \frac{a_i s_i}{r_i} + \frac{b_i c_i s_i (1-s_j)}{r_i\left[b_i s_i + c_i(1-s_j) + r_i\right]}.$$

So we have

$$\frac{\partial U_i}{\partial r_i} = W \log A_i - \frac{W A_i^{-1}}{\ln 2}\left(\frac{a_i s_i}{r_i} + \frac{b_i c_i s_i (1-s_j)\left[b_i s_i + c_i\left(1-s_j\right) + 2r_i\right]}{r_i\left[b_i s_i + c_i(1-s_j) + r_i\right]^2}\right) \quad \text{(A12)}$$

$$\frac{\partial^2 U_i}{\partial r_i^2} = \frac{W A_i^{-1}}{\ln 2}\frac{2b_i c_i s_i (1-s_j)}{(b_i s_i + c_i(1-s_j) + r_i)^3} - \frac{W A_i^{-2}}{\ln 2}[A_i - 1 + \frac{b_i c_i s_i (1-s_j)}{(b_i s_i + c_i(1-s_j) + r_i)^2}]^2 \quad \text{(A13)}$$

then $\frac{\partial^2 U_i}{\partial r_i^2} < 0$. Therefore, $U_i(r_i)$ is concave for r_i.

Observe that the constraint set is convex. So if $U_1(s_1, s_2)$ is proved to be concave for s_1 and s_2, Theorem 1 will be proved. For simplified representation, we define $f_1(s_1) = 1/s_1$ and $f_2(s_2) = 1/(1-s_2)$. For $f_1(s_1)$ and $f_2(s_2)$ are convex function. So $f_3(s_1,s_2) = b_1 f_2(s_2) + c_1 f_1(s_1) + r_1 f_1(s_1) f_2(s_2)$ is convex and $f_3(s_1,s_2)^{-1}$ is concave. So we have

$$U_1(s_1,s_2) = r_1 W \log\left(1 + \frac{a_1 s_1}{r_1} + \frac{b_1 c_1}{r_1 f_3(s_1,s_2)}\right) \quad \text{(A14)}$$

Furthermore, $f(u) = \log(1+u), \forall u > 0$ is monotone increasing concave function. Since the compound function $f(u) = \log(1+u(x,y))$ is concave if $u(x,y)$ is concave and $u(x,y) > 0$. Considering a positive linear combination of concave functions is concave. This way, $U_1(s_1,s_2)$ is proved to be concave for s_1 and s_2.

8.2 APPENDIX B: PROOF OF PROPOSITION 1

1. Positivity. It is obvious that $I_i(\tilde{r}_i) > 0$.

2. Monotonicity. If $\tilde{r}_i > \tilde{r}_i'$, then $I_i(\tilde{r}_i) \geq I_i(\tilde{r}_i')$.

For R_{ij}^{AF} and R_{ji}^{AF}, by taking the derivative to r_i respectively, we have

$$\frac{\partial R_{ij}^{AF}}{\partial r_i} = -\frac{W A_i^{-1}}{\ln 2}\left(\frac{a_i s_i}{r_i^2} + \frac{b_i c_i s_i (1-s_j)\left[b_i s_i + c_i\left(1-s_j\right) + 2r_i\right]}{r_i^2\left[b_i s_i + c_i(1-s_j) + r_i\right]^2}\right) \quad \text{(B15)}$$

and

$$\frac{\partial R_{ji}^{AF}}{\partial r_i} = \frac{W A_j^{-1}}{\ln 2}\left(\frac{a_j s_j}{(1-r_i)^2} + \frac{b_j c_j s_j (1-s_i)\left[b_j s_j + c_j\left(1-s_i\right) + 2\left(1-r_i\right)\right]}{(1-r_i)^2\left[b_j s_j + c_j(1-s_i) + 1 - r_i\right]^2}\right) \quad \text{(B16)}$$

So R_{ij}^{AF} is monotone decreasing function and R_{ji}^{AF} is monotone increasing function for r_i. Then, is $R_i^D\left(R_{ij}^{AF}\right)^{-1} - R_j^D\left(R_{ji}^{AF}\right)^{-1}$ monotone increasing function for r_i. Therefore, $I_i(\tilde{r}_i)$ is monotone increasing function for $\tilde{r}_i$.

3. Scalability.

For all $\alpha > 1$, let $\Delta I = \alpha I_i(\tilde{r}_i) - I_i(\alpha \tilde{r}_i)$.

Since $U_i(r_i)$ is monotone increasing function for r_i. $U_j(1-r_i)$ is monotone decreasing function. So we have

$$\alpha R_{ij}^{AF}(\alpha \tilde{r}_i) = \frac{\alpha \tilde{r}_i R_{ij}^{AF}(\alpha \tilde{r}_i)}{\tilde{r}_i} > R_{ij}^{AF}(\tilde{r}_i) \quad \text{(B17)}$$

and

$$(1-\alpha\tilde{r}_i)R_{ji}^{AF}\left(1-\alpha\tilde{r}_i\right) < (1-\tilde{r}_i)R_{ji}^{AF}\left(1-\tilde{r}_i\right) \tag{B18}$$

Then, we have

$$\Delta I = \frac{\alpha-1}{2} + R_i^D \frac{\alpha R_{ij}^{AF}\left(\alpha\tilde{r}_i\right) - R_{ij}^{AF}\left(\tilde{r}_i\right)}{2R_{ij}^{AF}\left(\tilde{r}_i\right)R_{ij}^{AF}\left(\alpha\tilde{r}_i\right)} + R_j^D \frac{R_{ji}^{AF}\left(\tilde{r}_i\right) - \alpha R_{ji}^{AF}\left(\alpha\tilde{r}_i\right)}{2R_{ji}^{AF}\left(\alpha\tilde{r}_i\right)R_{ji}^{AF}\left(\tilde{r}_i\right)} \tag{B19}$$

$$\Delta I > \frac{\alpha-1}{2} + R_j^D \frac{R_{ji}^{AF}\left(\tilde{r}_i\right) - \alpha R_{ji}^{AF}\left(\alpha\tilde{r}_i\right)}{2R_{ji}^{AF}\left(\alpha\tilde{r}_i\right)R_{ji}^{AF}\left(\tilde{r}_i\right)} \tag{B20}$$

$$\Delta I > \frac{\alpha-1}{2}\left[1 - \frac{R_j^D}{(1-\alpha\tilde{r}_i)R_{ji}^{AF}\left(\alpha\tilde{r}_i\right)}\right] > 0 \tag{B21}$$

For $(1-\alpha\tilde{r}_i)R_{ji}^{AF}\left(\alpha\tilde{r}_i\right) > R_j^D$, which is the cooperation condition. Therefore, we can claim that $\alpha I_i\left(\tilde{r}_i\right) > I_i\left(\alpha\tilde{r}_i\right)$.

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