A Bayesian Game Analysis of Cooperative MAC with Incentive for Wireless Networks

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***Abstract*—In this paper, we analyze a cooperative medium access scheme in a wireless relaying network using Bayesian games, where the participating nodes are peers subject to the half-duplex constraint and they choose to cooperate or not cooperate based on its expected utility. We first set up a one-stage game and derive the ex-post utility. A two-stage game with incomplete information is further formulated to incorporate an incentive mechanism, which charges the cooperation requester and rewards the helper via adapting their channel access probabilities. We prove that the not-cooperating strategy can always achieve a Nash equilibrium (NE) in one-stage and two-stage games as long as the access cost is constrained. More importantly, we derive the sufficient conditions so that cooperating is an NE strategy and supports higher utility than the not-cooperating strategy. Numerical results are presented to validate our analysis and demonstrate that optimal tuning factors can be determined to ensure NE and maximize system utility.**

***Index Terms*—Cooperative wireless communications, cooperative MAC, incentive, Bayesian game, Nash equilibrium.**

I. Introduction and Related Work

Taking advantage of the broadcast nature of wireless transmission, cooperative communications can achieve special diversity by having helper nodes relay overheard packets. Many studies on cooperative transmission have a common assumption that if a node is able to help, it chooses to help [1,2]. In reality, mobile devices may belong to different owners. Even if a node is capable of helping, it may decline a cooperation request although there could be high benefit in the long run. Thus, it is important to investigate cooperative medium access control (MAC) with incentive consideration [3,4]. An incentive mechanism can 1) charge the requester certain cost to prevent it from abusing resources; and 2) reward the helper with payoff to stimulate its participation in cooperation [5].

Game theory is a powerful tool to model and analyze such a mutual decision-making process. It has been widely applied to study different layers of wireless networks [6,7]. One of the earliest works using game theory to analyze the MAC protocol is [8]. In [9], slotted Aloha is also modeled as a game among contending users for channel access. The carrier sensing multiple access with collision avoidance (CSMA/CA) protocol is modeled and analyzed in a game-theoretical fashion in [10]. The decode-and-forward (DF) cooperative transmission strategy is studied in [11] as traditional repeated games and different utility functions are explored. Non-traditional games like evolutionary coalitional games are also gaining more attention in wireless network analysis, such as in [12,13]

This research was supported in part by Natural Sciences and Engineering Research Council (NSERC) of Canada.

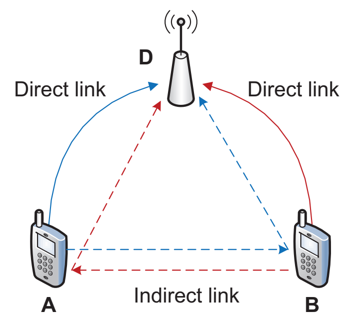


Fig. 1. Network topology.

In this paper, we study a cooperative MAC protocol based on slotted Aloha using Bayesian game models. Wireless nodes are assumed to be peers and subject to the half-duplex constraint, i.e., there are no dedicated helpers. Further taking into account incentive for participating nodes, we consider a pair of tuning factors to adapt channel access probabilities. Our game analysis proves that the not-cooperating strategy can achieve a Nash equilibrium (NE) when the access cost is low enough. Moreover, we derive the sufficient conditions which guarantee cooperating is an NE strategy. The conditions are extended to further ensure that the cooperating strategy supports a higher utility than the not-cooperating strategy. Numerical results demonstrate the efficiency of our analysis and determination of optimal tuning factors to maximize system utility.

The remainder of this paper is organized as follows. In Section II, we introduce the system model and game formulation. The one-stage and two-stage games are analyzed in Section III. In Section IV, numerical results are presented and discussed, followed by conclusions in Section V.

II. System Model and Problem Formulation

In this section, we first define the system model with cooperative transmission. Then, a basic one-stage game is introduced. A two-stage game further extends it considering an incentive mechanism.

TABLE I
STATES OF REQUESTER AND HELPER.

State of h	Packet arrival at t_1 or t_2?	Occurrence probability
1	No	$\theta_{h1} = (1-\lambda_h)^2$
2	Yes	$\theta_{h2} = 1-(1-\lambda_h)^2$
State of r	Packet arrival at t_2?	Occurrence probability
1	No	$\theta_{r1} = 1-\lambda_r$
2	Yes	$\theta_{r2} = \lambda_r$

A. System Model

Consider a cooperative scenario in Fig. 1, where there are a set of peer nodes $\mathbb{N} = \{A, B\}$ and a destination node D. Node A and B are peers, which means none is a dedicated helper to the other. Time is slotted and all nodes are subject to a half-duplex constraint, which means that during a time slot, a node cannot transmit and receive packets simultaneously. For any node n $(n \in \mathbb{N})$, the system setup is given as below.

- ***Packet arrival probability.*** When node n has a packet arrival in a time slot with a probability λ_n, it attempts to access the channel and remains silent otherwise.
- ***Channel access probability.*** Assuming channel access with slotted Aloha, when a packet arrives, node n accesses the channel and transmits the packet with a probability p_n, where $0 < p_{\min} \leq p_n \leq p_{\max} < 1$. Here, $p_{\min}$ and $p_{\max}$ are the lower and upper bounds of channel access probabilities to be adapted with traffic demands. Transmission is only successful without collision when only one node transmits.
- ***Transmission success probability.*** Let s_n denote the probability that that a packet is successfully received and decoded at the destination D over the direct link. On the other hand, the success probability over the indirect link with cooperation is denoted by s_{nm}, where n is the node that requests cooperative transmission, referred to as ***the requester***, and m is the node that accepts the request and provides relaying for n, referred to as ***the helper***. Here, we assume $s_{mn} > s_m$ for any $m, n \in \mathbb{N}, m \neq n)$.

B. Bayesian One-Stage Game and Its Ex-post Utility

Given the half-duplex constraint, cooperation agreement cannot be decided at the requester and the helper simultaneously within one time slot. Hence, we consider two time slots t_1 and t_2 in a one-stage game, which is formulated as follows.

- ***Node state.*** Depending on whether a node has a packet in the transmit buffer in a time slot, Table I shows the possible states at the requester r and the helper h. In the one-stage game formulation, we assume the node states are *ex-post*, which means r knows the state of h and vice versa. We relax this assumption in the two-stage game formation in Section II-C.
- ***Action set.*** Each node can choose to cooperate $(\mathcal{C})$ or not cooperate $(\mathcal{NC})$ as its action. The pair of actions of the requester and the helper are denoted by (a_r, a_h), where a_r and a_h represent the action of the requester in t_1 and that of the helper in t_2, respectively. Here, $a_r, a_h \in \{\mathcal{C}, \mathcal{NC}\}$.
- ***Utility and access cost.*** Utility is the mathematical abstraction of a user's overall benefit. Consider a non-negative monotonically increasing function $v(s)$ to quantify a node's gain on certain transmission success probability s, given $v(s) \geq 0$ and $v(0) = 0$. Subject to an access cost $c > 0$ for transmitting a packet, we evaluate the overall utility by $v(s) - c$.

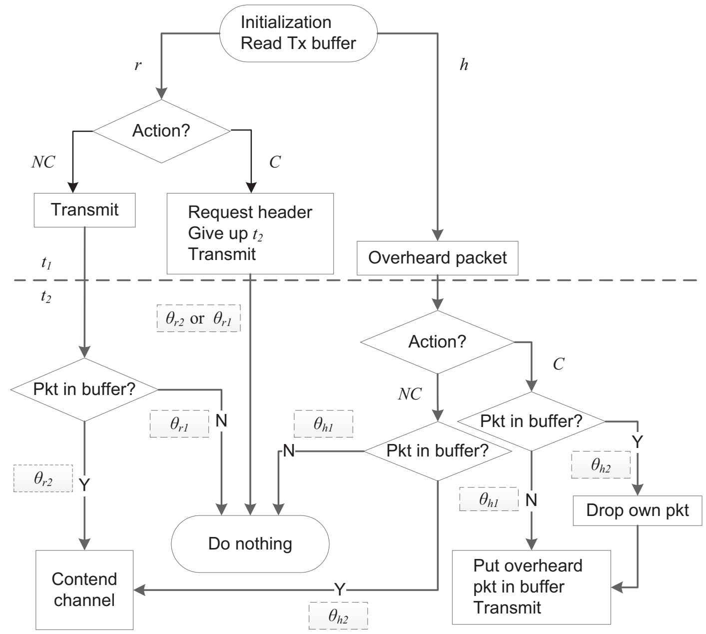


Fig. 2. One-stage game process for cooperative transmission.

The cooperative transmission process in the one-stage game is depicted in Fig. 2 which shows an example with node A as the requester r and node B as the helper h. At t_1, since A is the requester, A has a packet in its transmit buffer and A has captures the channel access in that slot. If A chooses the cooperating action $\mathcal{C}$, it piggybacks cooperation information in the packet header and deliberately gives up access contention in t_2 no matter what state it stays in t_2. Although B may have its own packet to transmit in t_2, B transmits the packet overheard in t_1 without contention in t_2, if B chooses the cooperating action $\mathcal{C}$. In this circumstance, A's utility is $v(s_{AB}) - c$ and B's utility is $-c$ since it transmits A's packet instead of its own. Generally, when the requester node r starts the game, we denote the utility of the requester r and that of the helper h by $U^{ij}_{r|r}(a_r, a_h)$ and $U^{ij}_{h|r}(a_r, a_h)$, respectively, for the pair of actions (a_r, a_h), given the requester's state i and the helper's state j, $i, j \in \{1, 2\}$. The *ex-post* utilities of the one-stage game are given in (1)-(8).

C. Two-Stage Game with Incomplete Information

Further considering the following properties, we extend the one-stage game to a two-stage game:

- ***Requester uncertainty.*** In the two-stage game, the requester of each stage is not necessarily the same. For example, even if A is the requester at the first stage, it

$$U^{ij}_{r|r}(\mathcal{C},\mathcal{C}) = v(s_{rh}) - c,\ i,j=1,2 \quad (1)$$

$$U^{ij}_{r|r}(\mathcal{C},\mathcal{NC}) = v(s_r) - c,\ i,j=1,2 \quad (2)$$

$$U^{ij}_{r|r}(\mathcal{NC},\mathcal{C}) = \quad (3)$$

$$\begin{cases} p_h(v(s_{rh})-c) + (1-p_h)[v(s_r)-c],\ i=1, j=1,2 \\ p_r p_h(v(s_r)-2c) + (1-p_r)p_h[v(s_{rh})-c] \\ \quad + p_r(1-p_h)[2v(s_r)-2c] \\ \quad + (1-p_r)(1-p_h)[v(s_r)-c],\ i=2, j=1,2 \end{cases}$$

$$U^{ij}_{r|r}(\mathcal{NC},\mathcal{NC}) = \quad (4)$$

$$\begin{cases} v(s_r)-c,\ i=1, j=1,2 \\ v(s_r)-c+p_r[v(s_r)-c],\ i=2, j=1 \\ v(s_r)-c-p_r p_h c + p_r(1-p_h)[v(s_r)-c],\ i=2, j=2 \end{cases}$$

$$U^{ij}_{h|r}(\mathcal{C},\mathcal{C}) = -c,\ i,j=1,2 \quad (5)$$

$$U^{ij}_{h|r}(\mathcal{NC},\mathcal{C}) = -p_h c,\ i,j=1,2 \quad (6)$$

$$U^{ij}_{h|r}(\mathcal{C},\mathcal{NC}) = \quad (7)$$

$$\begin{cases} 0,\ i=1,2, j=1 \\ p_h[v(s_h)-c],\ i=1,2, j=2 \end{cases}$$

$$U^{ij}_{h|r}(\mathcal{NC},\mathcal{NC}) = \quad (8)$$

$$\begin{cases} 0,\ i=1,2, j=1 \\ p_h[v(s_h)-c],\ i=1, j=2 \\ -p_r p_h c + p_h(1-p_r)[v(s_h)-c],\ i=2, j=2 \end{cases}$$

Fig. 3. *Ex-post* utilities of the one-stage game.

has to contend to start the second stage.

- ***Incentive mechanism.*** An incentive mechanism is incoporated to prevent the requester r from abusing resources and to stimulate the helper h to cooperate. Specifically, two tuning factors μ and ε are defined. If r and h choose actions $(\mathcal{C},\mathcal{C})$ at the first stage, p_r is updated to μp_r at the second stage and p_h to εp_h , where $\frac{p_{\min}}{p_r} \leq \mu \leq 1$ and $1 \leq \varepsilon \leq \frac{p_{\max}}{p_h}$. If r and h take other actions, p_r and p_h keep unchanged. In this manner, r decreases its contention privilege to exchange for the relaying of h, while h is rewarded with a higher channel access probability for its cooperative transmission at the first stage.
- ***Incomplete information.*** As seen in Fig. 2, the game is actually *ex-ante* to r: when r takes its action, it knows neither it own state nor h's state. The game is *interim* to h, since when h takes its action at t_2, it has already known its own state but is not aware of r's state. In the two-stage game, each node knows its exact state at the first stage, but cannot predict its state at the second stage. Their actions are decided at the beginning of the two-stage game, denoted by $(a_{n1} - a_{n2})$, where a_{ni} is the action that node n decides to take at the i^{th} stage.

Without loss of generality, consider A as the requester and B as the helper in the two-stage game. Given the state i ($i \in \{1,2\}$) of A and state j ($j \in \{1,2\}$) of B at the beginning of the game, we obtain the expected *interim* utility of A and B:

$$\overline{U}^i_A(a_{A1}-a_{A2}, a_{B1}-a_{B2}) = V^i_A(a_{A1},a_{B1}) + W_A(a_{A2},a_{B2}) \quad (9)$$

$$\overline{U}^j_B(a_{A1}-a_{A2}, a_{B1}-a_{B2}) = V^j_B(a_{A1},a_{B1}) + W_B(a_{A2},a_{B2}) \quad (10)$$

where

$$V^i_A(a_{A1},a_{B1}) = \mathbf{\Theta}_B \mathbf{M}^{Ai}_A(a_{A1},a_{B1}) \quad (11)$$

$$V^j_B(a_{A1},a_{B1}) = \mathbf{\Phi}_A \mathbf{N}^{Aj}_B(a_{A1},a_{B1}) \quad (12)$$

$$\begin{aligned} &W_A(a_{A2},a_{B2}) \\ &= \eta \mathbf{\Phi}_A \left[\mathbf{\Theta}_B \mathbf{M}^{A1}_A(a_{A2},a_{B2}), \quad \mathbf{\Theta}_B \mathbf{M}^{A2}_A(a_{A2},a_{B2})\right]^T \\ &\quad + (1-\eta)\mathbf{\Theta}_A \left[\mathbf{\Phi}_B \mathbf{N}^{B1}_A(a_{B2},a_{A2}), \quad \mathbf{\Phi}_B \mathbf{N}^{B2}_A(a_{B2},a_{A2})\right]^T \\ &W_B(a_{A2},a_{B2}) \\ &= \eta \mathbf{\Theta}_B \left[\mathbf{\Phi}_A \mathbf{N}^{A1}_B(a_{A2},a_{B2}), \quad \mathbf{\Phi}_A \mathbf{N}^{A2}_B(a_{A2},a_{B2})\right]^T \\ &\quad + (1-\eta)\mathbf{\Phi}_B \left[\mathbf{\Theta}_A \mathbf{M}^{B1}_B(a_{B2},a_{A2}), \quad \mathbf{\Theta}_A \mathbf{M}^{B2}_B(a_{B2},a_{A2})\right]^T . \end{aligned}$$

Here, η is the probability that the game is started by A at the second stage, given by

$$\eta = \begin{cases} \eta_1 = \dfrac{\mu p_r(1-\varepsilon p_h)}{\mu p_r(1-\varepsilon p_h) + \varepsilon p_h(1-\mu p_r)}, & a_{A1}, a_{B1} = \mathcal{C} \\ \eta_2 = \dfrac{p_r(1-p_h)}{p_r(1-p_h)+p_h(1-p_r)}, & \text{otherwise} \end{cases} \quad (13)$$

while for any $m, n \in \mathbb{N}, k=1,2$, $\mathbf{\Phi}_n$,$\mathbf{\Theta}_n$ $\mathbf{M}^{nk}_m(a_r,a_h)$, and $\mathbf{N}^{nk}_m(a_r,a_h)$ are given by

$$\mathbf{\Phi}_n = \left[1-\lambda_n, \lambda_n\right]$$

$$\mathbf{\Theta}_n = \left[(1-\lambda_n)^2, 1-(1-\lambda_n)^2\right]$$

$$\mathbf{M}^{nk}_m(a_r,a_h) = \begin{bmatrix} U^{k1}_{m|n}(a_r,a_h) \\ U^{k2}_{m|n}(a_r,a_h) \end{bmatrix} \quad (14)$$

$$\mathbf{N}^{nk}_m(a_r,a_h) = \begin{bmatrix} U^{1k}_{m|n}(a_r,a_h) \\ U^{2k}_{m|n}(a_r,a_h) \end{bmatrix} . \quad (15)$$

Then, we obtain the *ex-ante* expected utility of A as

$$\begin{aligned} &\overline{U}_A(a_{A1}-a_{A2}, a_{B1}-a_{B2}) \\ &= \mathbf{\Phi}_A \begin{bmatrix} \overline{U}^1_A(a_{A1}-a_{A2}, a_{B1}-a_{B2}) \\ \overline{U}^2_A(a_{A1}-a_{A2}, a_{B1}-a_{B2}) \end{bmatrix} . \end{aligned} \quad (16)$$

If the incentive mechanism is incorporated into the game, the tuned access probabilities μp_r and εp_h are applied to (1)-(8), and we use the notations $\tilde{\mathbf{M}}^{nk}_m(a_r,a_h)$ and $\tilde{\mathbf{N}}^{nk}_m(a_r,a_h)$.

III. Bayesian Nash Equilibrium Analysis

In this section, we analyze the Nash equilibriums for the one-stage and two-stage games. Specifically, we first derive the condition under which $(\mathcal{NC}, \mathcal{NC})$ is an *ex-post* NE strategy of the one-stage game. Based on that, we further show $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ is an NE of the two-stage game. Moreover, we are interested in the case where cooperation is performed in the first stage of the two-stage game, i.e., $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})$. We thus derive the conditions for $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})$ to be an NE and to provide a higher system utility than $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$.

A. Not-Cooperating Strategy

Proposition 1. *Given the upper bound $p_{\max}$ of access probability, $(\mathcal{NC}, \mathcal{NC})$ is an* ex-post *NE of one-stage game if*

$$c \leq \min_{n\in\mathbb{N}} \left[(1-p_{\max})v(s_n)\right]. \tag{17}$$

Proof. The action strategy $(\mathcal{NC}, \mathcal{NC})$ is an ex-post NE, if and only if for any $i, j \in \{1, 2\}$

$$U_r^{ij}(\mathcal{NC},\mathcal{NC}) \geq U_r^{ij}(\mathcal{C},\mathcal{NC}) \tag{18}$$
$$U_h^{ij}(\mathcal{NC},\mathcal{NC}) \geq U_h^{ij}(\mathcal{NC},\mathcal{C}). \tag{19}$$

Obviously, (18) always holds when $i = 1, j \in \{1, 2\}$. For other cases, the satisfaction of (18) requires

$$p_r\Big[v(s_r) - c\Big] \geq 0, \quad i = 2, j = 1 \tag{20}$$
$$p_r\big[(1-p_h)v(s_r) - c\big] \geq 0, \quad i = 2, j = 2 \tag{21}$$

When (17) holds, since $0 \leq p_h \leq p_{\max}$, $c \leq (1 - p_{\max})v(s_n) \leq (1 - p_h)v(s_n) \leq v(s_n)$. Apparently, both (20) and (21) are satisfied. Similarly, (19) can be proved. □

Proposition 2. *If $(\mathcal{NC}, \mathcal{NC})$ is an* ex-post *NE of the one-stage game, the following equations hold for any $n \in \mathbb{N}, k \in \{1, 2\}$*

$$V_n^k(\mathcal{NC},\mathcal{NC}) \geq V_n^k(\mathcal{C},\mathcal{NC}) \tag{22}$$
$$W_n(\mathcal{NC},\mathcal{NC}) \geq W_n(\mathcal{C},\mathcal{NC}). \tag{23}$$

Proof. If $(\mathcal{NC}, \mathcal{NC})$ is an ex-post NE of the one-stage game, we have (18) and (19) according to Proposition 1. Based on (11), (14) and (18), we have

$$\mathbf{M}_n^{nk}(\mathcal{NC},\mathcal{NC}) \geq \mathbf{M}_n^{nk}(\mathcal{C},\mathcal{NC}).$$

Based on (12), (15) and (19), we have

$$\mathbf{N}_m^{nj}(\mathcal{NC},\mathcal{NC}) \geq \mathbf{N}_m^{nj}(\mathcal{NC},\mathcal{C}).$$

Therefore,

$$V_n^i(\mathcal{NC},\mathcal{NC}) - V_n^i(\mathcal{C},\mathcal{NC}) = \begin{cases} \mathbf{\Theta}_B\Big[\mathbf{M}_n^{ni}(\mathcal{NC},\mathcal{NC}) - \mathbf{M}_n^{ni}(\mathcal{C},\mathcal{NC})\Big], \text{if } n = A \\ \mathbf{\Phi}_A\Big[\mathbf{N}_n^{ni}(\mathcal{NC},\mathcal{NC}) - \mathbf{N}_n^{ni}(\mathcal{C},\mathcal{NC})\Big], \text{if } n = B \end{cases} \geq 0.$$

Thus, (22) is proved. We can prove (23) similarly. □

Lemma 1. *Given (17), $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ is an NE of the two-stage game.*

Proof. To prove $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ is an NE, we first prove that, for any $(a_{A1} - a_{A2}), (a_{B1} - a_{B2}) \in \{(\mathcal{C}-\mathcal{C}), (\mathcal{C}-\mathcal{NC}), (\mathcal{NC}-\mathcal{C})\}$, and $i, j \in \{1, 2\}$, the following equations hold

$$\overline{U}_A^i(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}) \geq \overline{U}_A^i(a_{A1}-a_{A2},\mathcal{NC}-\mathcal{NC}) \tag{24}$$

$$\overline{U}_B^j(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}) \geq \overline{U}_B^j(\mathcal{NC}-\mathcal{NC},a_{B1}-a_{B2}). \tag{25}$$

Take $(a_{A1} - a_{A2}) = (\mathcal{C}-\mathcal{NC})$ as an example. Given (17), $(\mathcal{NC}, \mathcal{NC})$ is an NE based on Proposition 1. Therefore, both (22) and (23) hold according to Proposition 2. Then, based on (9), (22) and (23), we have

$$\begin{aligned} &\overline{U}_A^i(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}) \\ &= V_A^i(\mathcal{NC},\mathcal{NC}) + W_A(\mathcal{NC},\mathcal{NC}) \\ &\geq V_A^i(\mathcal{C},\mathcal{NC}) + W_A(\mathcal{NC},\mathcal{NC}) \\ &= \overline{U}_A^i(\mathcal{C}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}). \end{aligned}$$

Similarly, based on (22) and (23), we can see that any $(a_{A1} - a_{A2}) \in \{(\mathcal{C}-\mathcal{C}), (\mathcal{NC}-\mathcal{C})\}$ satisfies (24). Following a similar procedure, we can prove (25) from (10), (22) and (23). Given (16) and (24), it is obvious that

$$\overline{U}_A(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}) \geq \overline{U}_A(a_{m1}-a_{m2},\mathcal{NC}-\mathcal{NC}).$$

Therefore, $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ is an NE. □

B. Cooperating Strategy

Besides the not-cooperating strategy for the two-stage game $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$, we are more interested in a cooperating strategy $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})$, where the player chooses to cooperate at the fist stage as "investment" and terminates the cooperation at the second stage as "collecting reward". Also, the access probability needs to be reset after the second stage, so both the requester and the helper expect some kind of closure settlement before the end of the game.

Lemma 2. *Define $\beta = \eta_1/\eta_2$, where η_1 and η_2 are defined in (13). With the tuning factors μ and ε for the access probabilities, $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})\}$ is an NE of the two-stage game if (17) and the following conditions are satisfied*

$$\beta < 1 \tag{26}$$
$$\beta\varepsilon\mu \leq 1 \tag{27}$$
$$\max(X_1, X_2) \leq c \leq \min(Y_1, Y_2) \tag{28}$$

where X_1, X_2, Y_1 and Y_2 are given by

$$X_1 = v(s_A) - \frac{(1-p_B)\big[v(s_{AB}) - v(s_A)\big]}{(1-\beta)\eta_2 + p_r(3\lambda_A - \lambda_A^2)} \tag{29}$$
$$X_2 = v(s_A) - p_B v(s_{AB}) \tag{30}$$
$$Y_1 = \big[(1-\beta)\eta_2 - p_B\big]\big[v(s_B) - c\big] \tag{31}$$
$$Y_2 = Y_1 - p_B\eta_2(1-\theta_{B1})(1-\beta\varepsilon)\big[v(s_B) - c\big]. \tag{32}$$

Proof. The proof of Lemma 2 is given in Appendix A. □

C. Not-Cooperating vs. Cooperating

Proposition 3. *Given Lemma 2, both $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})$ and $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ are NEs of the two-stage game.*

Proof. Note that one of the conditions for Lemma 2 to hold is (17), which is the condition for Lemma 1. This means, if the conditions for Lemma 2 are satisfied, (17) must be true so that $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ is an NE according to Lemma 1. As a result, both $(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC})$ and $(\mathcal{NC}-\mathcal{NC}, \mathcal{NC}-\mathcal{NC})$ are NEs when the conditions for Lemma 2 hold. □

Given Proposition 3, there is a natural question which NE strategy provides a higher utility. Comparing the two strategies, we obtain the following Lemma.

Lemma 3. *When both ($\mathcal{C}-\mathcal{NC}$, $\mathcal{C}-\mathcal{NC}$) and ($\mathcal{NC}-\mathcal{NC}$, $\mathcal{NC}-\mathcal{NC}$) are NE strategies of the two-stage game,($\mathcal{C}-\mathcal{NC}$, $\mathcal{C}-\mathcal{NC}$) achieves a higher utility for both players if (17), (26), (27), and the following equation hold*

$$\max(X_1, X_2, X_3) \leq c \leq \min(Y_1, Y_2) \tag{33}$$

where

$$X_3 = v(s_A) - \frac{v(s_{AB}) - (1+p_A)v(s_A)}{(1-\beta)\eta_2 + p_A(3\lambda_A - \lambda_A^2)}. \tag{34}$$

Proof. The proof of Lemma 3 is given in Appendix B. □

IV. Numerical Results

In this section, we provide some numerical results on the lemmas we have derived. Specifically, we first demonstrate the efficiency of the conditions in Lemma 3 with different traffic load. Then, we compare the utility of the cooperating NE strategy and the not-cooperating NE strategy. Finally, we investigate how to maximize system utility by appropriately setting the tuning factors μ and ε for the incentive mechanism.

A. Efficiency of Sufficient Conditions in Lemma 3

For the cooperative system in Fig. 1, we are interested in whether a pair of tuning factors μ and ε can be determined, so that both nodes A and B can apply such an incentive mechanism for the system to achieve an NE. Consider a gain function $v(s) = s$ for any $s \in \{s_A, s_B, s_{AB}, s_{BA}\}$. As defined in Section II-C, we have $\frac{p_{\min}}{p_A} \leq \mu \leq 1$ and $1 \leq \varepsilon \leq \frac{p_{\max}}{p_B}$. Inside these ranges, we test a large number of tuning factors (e.g., 2500 pairs of μ and ε). Let α_1 represent the number of pairs that can satisfy the *ex-post* NE conditions in (36), (37), (38), (39), (41) and (42), and α_2 represent the number of pairs that satisfy the sufficient conditions given in Lemma 3. We evaluate the efficiency of Lemma 3 by a factor defined as $\rho = \alpha_2/\alpha_1$. Fig. 4 shows how ρ varies with the traffic load from nodes A and B, which is represented by the packet arrival probability in one time slot. Here, we assume $\lambda_A = \lambda_B = \lambda$. We can see in Fig. 4 that when there is not a heavy traffic load at $\lambda = 0.1$, Lemma 3 has a high efficiency around 0.9. This implies that it is easy to obtain feasible μ and ε in such cases for the incentive mechanism to guarantee an NE. As the load becomes heavier, ρ drops gradually. Finally, when both nodes are almost saturated at $\lambda = 0.9$, ρ is around 0.3.

B. Not-Cooperating vs. Cooperating

In Section III-C, Lemma 3 gives the conditions for a cooperating strategy to achieve an NE and to guarantee a higher utility for both players when they are cooperating. Fig. 5 shows the numerical results comparing the utility of the cooperating and not-cooperating NE strategies, with the tuning factors μ and ε determined by Lemma 3. In both Fig. 5(a) and Fig. 5(b), we see that the utility with cooperating is constantly higher than that of not-cooperating. In Fig. 5(a), it is observed that the utility slightly increases with μ. Intuitively, the higher μ, the less the requester A needs to pay for the help of B, and thus the higher the utility of A. On the other hand, with ε increasing, A gets slightly less utility, because B takes more

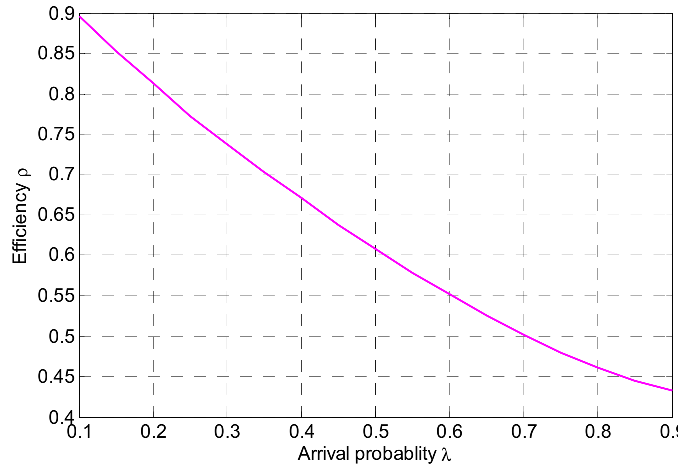


Fig. 4. Efficiency ρ of Lemma 3 vs. packet arrival probability with $\lambda_A = \lambda_B = \lambda$, $c = 0.01$, $p_{\max} = 0.9$, $p_{\min} = 0.1$, $p_A = p_B = 0.3$, $v(s_{AB}) = v_(s_{BA}) = 0.7$, $v(s_A) = 0.1$, and $v(s_B) = 0.5$.

reward by having a larger channel access probability, which relatively decreases the chance of A to access the channel. An opposite trend is found in Fig. 5(b), since A and B are competing. Nonetheless, mutual benefit in terms of higher utility can still be achieved at both sides with cooperating.

C. System Utility and Its Maximization

Lemma 3 can provide multiple feasible pairs of μ and ε. Fig. 5 in Section IV-B shows that A's utility generally increases with μ, while B's utility increases with ε. If A and B are allowed to choose μ and ε selfishly, we can expect that A chooses the maximum possible μ and so does B. We call this "*selfish choice*". In contrast, from the system's perspective, the selfish choice is not always a good choice. Notice that, for any node $n \in \{A, B\}$, with the cooperating strategy ($\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC}$), we have

$$\overline{U}_n^1(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC}) = \overline{U}_n^2(\mathcal{C}-\mathcal{NC}, \mathcal{C}-\mathcal{NC}) = \overline{U}_n.$$

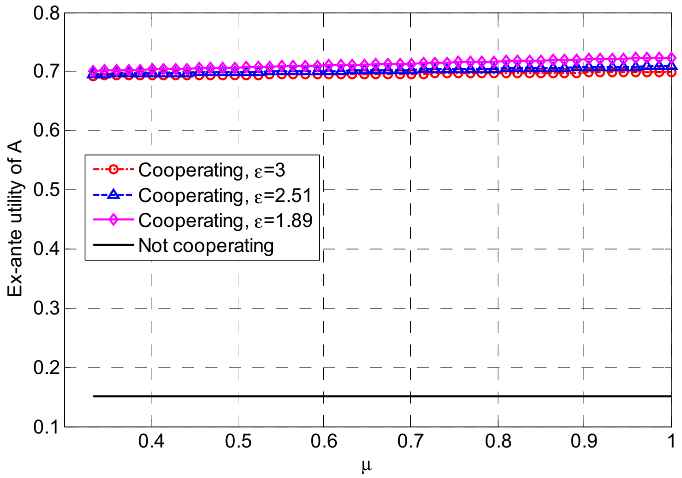
Thus, we define the system utility as

$$U_{sys}(\mu, \varepsilon) = \min\left(\frac{\overline{U}_A(\mu,\varepsilon)}{\max\limits_{\mu,\varepsilon}\overline{U}_A(\mu,\varepsilon)}, \frac{\overline{U}_B(\mu,\varepsilon)}{\max\limits_{\mu,\varepsilon}\overline{U}_B(\mu,\varepsilon)}\right) \tag{35}$$

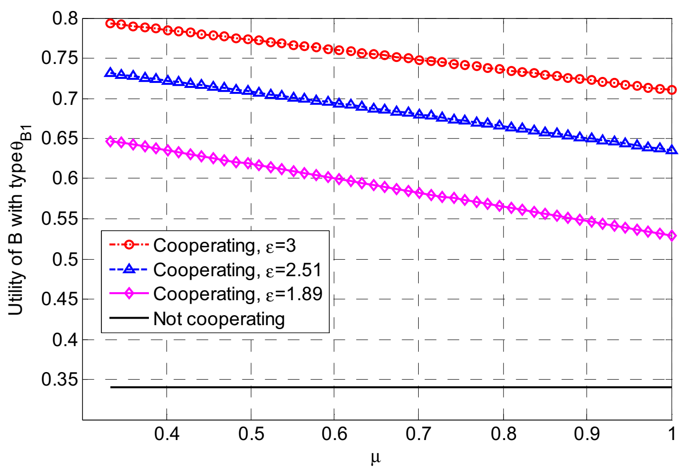
Among all feasible μ and ε, we find that there exists an optimal pair of $\tilde{\mu}$ and $\tilde{\varepsilon}$ that maximize (35). Fig. 6 shows the system utility achieved by the optimal pair with different traffic load. It can be seen that, as the traffic load is heavier, the system utility using the optimal pair becomes much greater than that using the selfish choice. Besides, the optimal pair also keeps a stable system utility, while selfish choice degrades the system utility significantly when the nodes are being saturated.

V. Conclusions

Even though cooperative transmission undoubtedly introduces diversity benefits, the selfish behavior needs to be properly addressed with an effective incentive mechanism so that both the requester node and the helper node can achieve higher utility via cooperation. Meanwhile, it is important to guarantee that the cooperative system achieves a stable Nash



(a) Ex-ante utility of requester A.



(b) Utility of helper B in state 2 with probability θ_{B1}.

Fig. 5. Utility of cooperating and not-cooperating NE strategies with $\lambda_A = \lambda_B = 0.8$, $c = 0.01$, $p_{\max} = 0.9$, $p_{\min} = 0.1$, $p_A = p_B = 0.3$, $v(s_{AB}) = v(s_{BA}) = 0.7$, $v(s_A) = 0.1$, and $v(s_B) = 0.5$.

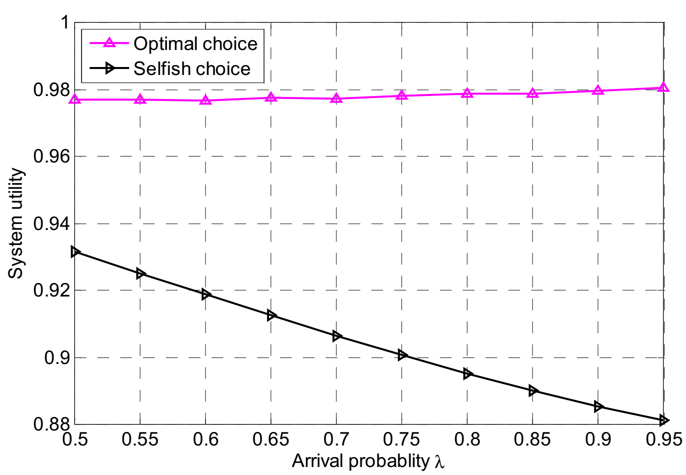


Fig. 6. System utility vs. packet arrival probability with $\lambda_A = \lambda_B = \lambda$, $c = 0.01$, $p_{\max} = 0.9$, $p_{\min} = 0.1$, $p_A = p_B = 0.3$, $v(s_{AB}) = v(s_{BA}) = 0.7$, $v(s_A) = 0.1$, and $v(s_B) = 0.5$.

equilibrium. In this paper, we model and analyze a simple cooperative MAC scheme based on slotted Aloha by Bayesian games. We start with a one-stage game and then extend it to a two-stage game considering incomplete information and an incentive mechanism. With solid analysis, we find that the not-cooperating strategy is always an NE as long as the access cost is constrained. Besides, we derive the sufficient conditions under which the cooperating strategy can also achieve an NE and even a higher utility than the not-cooperating strategy. Numerical results are provided to validate our analysis. We also evaluate the efficiency of the sufficient conditions to determine the tuning factors of the incentive mechanism. Optimal tuning factors rather than selfish choice can be obtained to maximize the system utility while maintaining system stability.

APPENDIX A
PROOF OF LEMMA 2

Proof. To prove Lemma 2, we need the following Proposition (4) and Proposition (5).

Proposition 4. *When (17) is satisfied, for any* $i, j \in \{1, 2\}$,

$$\overline{U}_A^i(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}) \geq \overline{U}_A^i(\mathcal{C}-\mathcal{C},\mathcal{C}-\mathcal{NC}) \quad (36)$$
$$\overline{U}_B^j(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}), \geq \overline{U}_B^j(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{C}). \quad (37)$$

Proof. According to (9) and Proposition 2, (36) can be proved as follows:

$$\begin{aligned}
&\overline{U}_A^i(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}) - \overline{U}_A^i(\mathcal{C}-\mathcal{C},\mathcal{C}-\mathcal{NC}) \\
&\quad = V_A^i(\mathcal{C},\mathcal{C}) + W_A(\mathcal{NC},\mathcal{NC}) - \left[V_A^i(\mathcal{C},\mathcal{C}) + W_A(\mathcal{C},\mathcal{NC})\right] \\
&\quad = W_A(\mathcal{NC},\mathcal{NC}) - W_A(\mathcal{C},\mathcal{NC}) \\
&\quad \geq 0.
\end{aligned}$$

Likewise, (37) can be proved from (10) and Proposition 2. □

Proposition 5. *When (17), (26), (27) and (28) are satisfied, the following equations hold for any* $i, j \in \{1, 2\}$ *and any* $(a_{A1} - a_{A2}), (a_{B1} - a_{B2}) \in \{(\mathcal{NC}-\mathcal{C}), (\mathcal{NC}-\mathcal{NC})\}$

$$\overline{U}_A^i(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}) \geq \overline{U}_A^i(a_{A1}-a_{A2},\mathcal{C}-\mathcal{NC}) \quad (38)$$
$$\overline{U}_B^j(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}) \geq \overline{U}_B^j(\mathcal{C}-\mathcal{NC},a_{B1}-a_{B2}). \quad (39)$$

Proof. Take the utility of A when $i = 1$ and $(a_{A1}-a_{A2}, a_{B1}-a_{B2}) = (\mathcal{NC}-\mathcal{C}, \mathcal{C}-\mathcal{NC})$ as an example. According to (9),

$$\begin{aligned}
&\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC}) = V_A^1(\mathcal{C},\mathcal{C}) + W_A(\mathcal{NC},\mathcal{NC}) \\
&\ = \eta_1 \mathbf{\Phi}_A \left[\mathbf{\Theta}_B \tilde{\mathbf{M}}_A^{A1}(\mathcal{NC},\mathcal{NC}), \quad \mathbf{\Theta}_B \tilde{\mathbf{M}}_A^{A2}(\mathcal{NC},\mathcal{NC})\right]^T \\
&\quad + (1-\eta_1)\mathbf{\Theta}_A \left[\mathbf{\Phi}_B \tilde{\mathbf{N}}_A^{B1}(\mathcal{NC},\mathcal{NC}), \quad \mathbf{\Phi}_B \tilde{\mathbf{N}}_A^{B2}(\mathcal{NC},\mathcal{NC})\right]^T \\
&\quad + \mathbf{\Theta}_B \mathbf{M}_A^{Ai}(\mathcal{C},\mathcal{C})
\end{aligned}$$

where η_1 is defined in (13). Similarly,

$$\begin{aligned}
&\overline{U}_A^1(\mathcal{NC}-\mathcal{C},\mathcal{C}-\mathcal{NC}) = V_A^1(\mathcal{NC},\mathcal{C}) + W_A(\mathcal{C},\mathcal{NC}) \\
&\ = \eta_2 \mathbf{\Phi}_A \left[\mathbf{\Theta}_B \mathbf{M}_A^{A1}(\mathcal{C},\mathcal{NC}), \quad \mathbf{\Theta}_B \mathbf{M}_A^{A2}(\mathcal{C},\mathcal{NC})\right]^T \\
&\quad + (1-\eta_2)\mathbf{\Theta}_A \left[\mathbf{\Phi}_B \mathbf{N}_A^{B1}(\mathcal{C},\mathcal{NC}), \quad \mathbf{\Phi}_B \mathbf{N}_A^{B2}(\mathcal{C},\mathcal{NC})\right]^T \\
&\quad + \mathbf{\Theta}_B \mathbf{M}_A^{Ai}(\mathcal{NC},\mathcal{C})
\end{aligned}$$

where η_2 is defined in (13). According to (1)-(8), (14) and (15), we have

$$\begin{aligned}
&\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})-\overline{U}_A^1(\mathcal{NC}-\mathcal{C},\mathcal{C}-\mathcal{NC})\\
&\quad=(1-p_B)\big[v(s_{AB})-v(s_A)\big]-(1-\beta)\eta_2\big[v(s_A)-c\big]\\
&\qquad+(1-\lambda_A)\big[1-(1-\lambda_B)^2\big]\beta\eta_2(\mu p_A)\big[v(s_A)-c\big]\\
&\qquad+\lambda_A\big[1-(1-\lambda_B)^2\big]\beta\eta_2(\mu p_A)\big[(1-\varepsilon p_B)v(s_A)-c\big]\\
&\qquad+(1-\lambda_A)\lambda_B(1-\beta\eta_2)(\mu p_A)\big[v(s_A)-c\big]\\
&\qquad+\lambda_A\lambda_B(1-\beta\eta_2)(\mu p_A)\big[(1-\varepsilon p_B)v(s_A)-c\big]\\
&\qquad+p_A(1-\eta_2)c
\end{aligned}$$

where $\beta=\eta_1/\eta_2$. As probabilities, p_A, p_B, μp_A, εp_B, λ_A, λ_B, $\eta_1=\beta\eta_2$, and η_2 all fall into the interval $[0,1]$. Examining all terms in the above equation, it is required that $\big[v(s_A)-c\big]\geq 0$, $\big[(1-\varepsilon p_B)v(s_A)-c\big]\geq 0$, and $(1-p_B)\big[v(s_{AB})-v(s_A)\big]\geq(1-\beta)\eta_2\big[v(s_A)-c\big]$, so that $\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^1(\mathcal{NC}-\mathcal{C},\mathcal{C}-\mathcal{NC})$. According to (17), we have $\big[v(s_A)-c\big]\geq 0$ and $\big[(1-\varepsilon p_B)v(s_A)-c\big]\geq 0$. For X_1 defined in (29), according to (28), $c\geq X_1$. That is,

$$X_1-c=\big[v(s_A)-c\big]-\frac{(1-p_B)\big[v(s_{AB})-v(s_A)\big]}{(1-\beta)\eta_2+p_r(3\lambda_A-\lambda_A^2)}\leq 0.$$

Given $\big[v(s_A)-c\big]\geq 0$, it is obvious that

$$\begin{aligned}
&0\leq v(s_A)-c\leq\frac{(1-p_B)\big[v(s_{AB})-v(s_A)\big]}{(1-\beta)\eta_2+p_r(3\lambda_A-\lambda_A^2)}\iff\\
&\big[(1-\beta)\eta_2\big]\big[v(s_A)-c\big]+\big[v(s_A)-c\big]\big[p_r(3\lambda_A-\lambda_A^2)\big]\\
&\qquad\leq(1-p_B)\Big[v(s_{AB})-v(s_A)\Big]
\end{aligned}$$

Since $0\leq\lambda_A\leq 1$, we know $3\lambda_A-\lambda_A^2\geq 0$. Thus, we prove $(1-p_B)\big[v(s_{AB})-v(s_A)\big]\geq(1-\beta)\eta_2\big[v(s_A)-c\big]$ and

$$\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^1(\mathcal{NC}-\mathcal{C},\mathcal{C}-\mathcal{NC}).\qquad(40)$$

Following this method, we can further obtain similar results for the other strategies in the following. Combining $c\geq X_1$, $c\geq X_2$, $c\leq Y_1$ and $c\leq Y_2$, we have (28). Thus, when (17), (26), (27) and (28) are satisfied, (38) and (39) are proved for Proposition (5).

$$\begin{aligned}
&\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^1(\mathcal{NC}-\mathcal{NC},\mathcal{C}-\mathcal{NC}),\text{if (17), (27), } c\geq X1\\
&\overline{U}_A^2(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^2(\mathcal{NC}-\mathcal{C},\mathcal{C}-\mathcal{NC}),\text{if (17), } c\geq X_1,\ c\geq X_2\\
&\overline{U}_A^2(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^2(\mathcal{NC}-\mathcal{NC},\mathcal{C}-\mathcal{NC}),\text{if (17), (27), } c\geq X_1,X_2\\
&\overline{U}_B^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_B^1(\mathcal{C}-\mathcal{NC},\mathcal{NC}-\mathcal{C}),\text{if (17), (26), } c\leq Y_1\\
&\overline{U}_B^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_B^1(\mathcal{C}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}),\text{if (27), } c\leq Y_2\\
&\overline{U}_B^2(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_B^2(\mathcal{C}-\mathcal{NC},\mathcal{NC}-\mathcal{C}),\text{if (17), (26), } c\leq Y_1\\
&\overline{U}_B^2(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_B^2(\mathcal{C}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}),\text{if (27), } c\leq Y_2
\end{aligned}$$

□

Finally, based on Proposition (4), Proposition (5) and (16), Lemma (2) can be proved. □

APPENDIX B
PROOF OF LEMMA 3

Proof. Since (33) ensures (28), when (17), (26), (27) and (33) are satisfied, Lemma 2 holds. According to Proportion 3, we know both $(\mathcal{C}-\mathcal{NC},\ \mathcal{C}-\mathcal{NC})$ and $(\mathcal{NC}-\mathcal{NC},\ \mathcal{NC}-\mathcal{NC})$ are NE strategies. Taking the utility of A when $i=2$ as an example, we compare the utilities of the two strategies as follows:

$$\begin{aligned}
&\overline{U}_A^2(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})-\overline{U}_A^2(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC})\\
&\quad\geq\lambda_A\big[1-(1-\lambda_B)^2\big]\eta_2 p_A(1-\beta\mu\varepsilon)v(s_A)\\
&\qquad+\Big[v(s_{AB})-(1+p_A)v(s_A)-(1-\beta)\eta_2\big(v(s_A)-c\big)\\
&\qquad-p_A(3\lambda_A-\lambda_A^2)\big(v(s_A)-c\big)\Big]
\end{aligned}$$

According to (33), $c\geq X_3$, where X_3 is given in (34). Thus, the second term in the righthand side of the above equation is no less than 0. Given (27), the first term is also non-negative. Likewise, we can prove $\overline{U}_A^1(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^1(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC})$ given (17), (27) and (28). Combining $c\geq X_3$ with (28), we have (33). Similar proof can also be provided for the utility of B. Therefore, given (17), (26), (27) and (33), for any $i,j\in\{1,2\}$,

$$\overline{U}_A^i(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_A^i(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC})\quad(41)$$

$$\overline{U}_B^j(\mathcal{C}-\mathcal{NC},\mathcal{C}-\mathcal{NC})\geq\overline{U}_B^j(\mathcal{NC}-\mathcal{NC},\mathcal{NC}-\mathcal{NC}).\quad(42)$$

Based on (16), (41) and (42), Lemma 3 is proved. □

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