Coalition Games with Cooperative Transmission: A Cure for the Curse of Boundary Nodes in Selfish Packet-Forwarding Wireless Networks

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***Abstract*—In wireless packet-forwarding networks with selfish nodes, application of a repeated game can induce the nodes to forward each others' packets, so that the network performance can be improved. However, the nodes on the boundary of such networks cannot benefit from this strategy, as the other nodes do not depend on them. This problem is sometimes known as *the curse of the boundary nodes*. To overcome this problem, an approach based on coalition games is proposed, in which the boundary nodes can use cooperative transmission to help the backbone nodes in the middle of the network. In return, the backbone nodes are willing to forward the boundary nodes' packets. Here, the concept of core is used to study the stability of the coalitions in such games. Then three types of fairness are investigated, namely, min-max fairness using nucleolus, average fairness using the Shapley function, and a newly proposed market fairness. Based on the specific problem addressed in this paper, market fairness is a new fairness concept involving fairness between multiple backbone nodes and multiple boundary nodes. Finally, a protocol is designed using both repeated games and coalition games. Simulation results show how boundary nodes and backbone nodes form coalitions according to different fairness criteria. The proposed protocol can improve the network connectivity by about 50%, compared with pure repeated game schemes.**

***Index Terms*—Game theory, coalition game, cooperative transmission, and packet forwarding network.**

I. Introduction

IN wireless networks with selfish nodes such as ad hoc networks, the nodes may not be willing to fully cooperate to accomplish the overall network goals. Specifically for the packet-forwarding problem, forwarding of other nodes' packets consumes a node's limited battery energy. Therefore, it may not be in a node's best interest to forward other's arriving packets. However, refusal to forward other's packets non-cooperatively will severely affect the network functionality and thereby impair a node's own performance. Hence, it is necessary to design a mechanism to enforce cooperation for packet forwarding among greedy and distributed nodes.

The packet-forwarding problem in ad hoc networks has been extensively studied in the literature. The fact that nodes act selfishly to optimize their own performance has motivated many researchers to apply game theory [1], [2] in solving this problem. Broadly speaking, the approaches used to encourage packet-forwarding can be categorized into two general types. The first type makes use of virtual payments. Pricing [3] and credit based method [4] fall into this first type. The second type of approach is related to personal and community enforcement to maintain the long-term relationship among nodes. Cooperation is sustained because defection against one node causes personal retaliation or sanction by others. *Watchdog* and *pathrater* are proposed in [5] to identify misbehaving nodes and deflect traffic around them. Reputation-based protocols are proposed in [6] and [7]. In [8], a model is considered to show cooperation among participating nodes. In [9], the question of whether cooperation for packet forwarding can exist without incentive mechanisms is answered using game theory and graph theory. Packet forwarding schemes using "tit for tat" schemes are proposed in [10]. In [11], a cartel maintenance framework is constructed for distributed rate control for wireless networks. In [12], self-learning repeated game approaches are constructed to enforce cooperation and to study better cooperation. Some recent work applying game theory to enhance energy-efficient behavior in infrastructure networks can be found in [13]–[16].

However, packet-forwarding networks are plagued by the so-called *curse of the boundary nodes*. The nodes at the boundary of the network must depend on the backbone nodes in the middle of the networks to forward their packets. On the other hand, the backbone nodes will not correspondingly depend on the boundary nodes. As a result, the backbone nodes do not worry about retaliation or lost reputation for not forwarding the packets of the boundary nodes. This fact causes the curse of the boundary nodes. In order to cure this curse, in this paper, we propose an approach based on cooperative game coalitions using cooperative transmission.

Recently, cooperative transmission [17] [18] has gained considerable attention as a transmit strategy for future wireless networks. The basic idea of cooperative transmission is that relay nodes can help a source node's transmission by relaying a replica of the source's information. Cooperative communications efficiently takes advantage of the broadcast nature of wireless networks, while exploiting the inherent spatial and multiuser diversities. The energy-efficient broadcast problem in wireless networks is considered in [19]. The work in [20] evaluates the cooperative diversity performance when the

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best relay is chosen according to the average signal-to-noise ratio (SNR), and the outage probability of relay selection based on instantaneous SNRs. In [21], the authors propose a distributed relay selection scheme that requires limited network knowledge with instantaneous SNRs. In [22], the relay assignment problem is solved for multiuser cooperative communications. In [23], cooperative resource allocation for orthogonal frequency division multiplexing (OFDM) is studied. A game theoretic approach for relay selection has been proposed in [24]. In [25], the sensor nodes can cooperate to form longer range communication links so as to bypass the energy-depleting nodes. As a result, the network life time can be greatly improved. In [26], centralized power allocation schemes are presented by assuming all the relay nodes helped. In [27], cooperative routing protocols are constructed based on non-cooperative routes.

Using cooperative transmission, boundary nodes can serve as relays and provide some transmission benefits for the backbone nodes that can be viewed as source nodes. In return, the boundary nodes are rewarded for packet-forwarding. To analyze the benefits and rewards, we investigate a game coalition that describes how much collective payoff a set of nodes can gain and how to divide this payoff. We investigate the stability and payoff division using concepts such as the core, nucleolus, and Shapley function. Three types of fairness are defined, namely, the min-max fairness using nucleolus, average fairness using the Shapley function, and our proposed market value fairness. Market fairness is a new fairness concept involving multiple backbone nodes and multiple boundary nodes, based on the specific problem treated in this paper. Then, we construct a protocol using both repeated games and coalition games. From the simulation results, we investigate how boundary nodes and backbone nodes form coalitions according to different fairness criteria. The proposed protocol can improve the network connectivity by about 50%, compared to the pure repeated game approach.

This paper is organized as follows: In Section II, repeated game approaches are reviewed and the curse of the boundary nodes is explained. In Section III, the cooperative transmission model is illustrated and the corresponding coalition games are constructed. Stability and three types of fairness are investigated. A protocol that exploits the properties of our approach is also proposed. Simulation results are shown in Section IV and conclusions are given in Section V.

II. Repeated Games and the Curse of Boundary Nodes

A wireless packet-forwarding network can be modeled as a directed graph $G(L, A)$, where L is the set of all nodes and A is the set of all directed links $(i, l), i, l \in L$. Each node i has several transmission destinations which are included in set D_i. To reach the destination j in D_i, the available routes form a *depending graph* G_i^j whose nodes represents the potential packet-forwarding nodes. The transmission from node i to node j depends on a subsect of the nodes in G_i^j for packet-forwarding. Notice that this dependency can be mutual. One node depends on the other node, while the other node can depend on this node as well. In general, this mutual dependency is common, especially for backbone nodes at the center of the network. In the remainder of this section, we will discuss how to make use of this mutual dependency for packet-forwarding using a repeated game, and then we will explain the curse of boundary nodes.

A. Repeated Games for Mutually Dependent Nodes

A repeated game is a special type of dynamic game (a game that is played multiple times). When the nodes interact by playing a similar static game (which is played only once) numerous times, the game is called a repeated game. Unlike a static game, a repeated game allows a strategy to be contingent on the past moves, thus allowing reputation effects and retribution, which give possibilities for cooperation. The game is defined as follows:

Definition 1: A T-period *repeated game* is a dynamic game in which, at each period t, the moves during periods $1, \ldots, t-1$ are known to every node. In such a game, the total discounted payoff for each node is computed by $\sum_{t=1}^{T} \beta^{t-1} u_i(t)$, where $u_i(t)$ denotes the payoff to node i at period t and where β is a discount factor. Note that β represents the node's patience or on the other hand how significantly the past affects the current payoff. If $T = \infty$, the game is referred as an infinitely-repeated game. The average payoff to node i is then given by:

$$u_i = (1 - \beta) \sum_{t=1}^{\infty} \beta^{t-1} u_i(t). \quad (1)$$

It is known that repeated games can be used to induce greedy nodes in communication networks to show cooperation. In packet-forwarding networks, if a greedy node does not forward the packets of other nodes, it can enjoy benefits such as power saving. However, this node will be punished by the other nodes in the future if it depends on the other nodes to forward its own packets. The benefit of greediness in the short term will be offset by the loss associated with punishment in the future. So the nodes will rather act cooperatively if the nodes are sufficiently patient. From the Folk theorem below, we infer that in an infinitely repeated game, any feasible outcome that gives each node a better payoff than the Nash equilibrium [1], [2] can be obtained.

Theorem 1: (*Folk Theorem* [1], [2]) Let $(\hat{u}_1, \ldots, \hat{u}_L)$ be the set of payoffs from a Nash equilibrium and let $(u_1, \ldots, u_L)$ be any feasible set of payoffs. There exists an equilibrium of the infinitely repeated game that attains any feasible solution $(u_1, \ldots, u_L)$ with $u_i \geq \hat{u}_i, \forall i$ as the average payoff, provided that β is sufficiently close to 1.

In the literature of packet-forwarding wireless networks, the conclusion of the above Folk theorem is achieved by several approaches. Tit-for-tat [8] [10] is proposed so that all mutually dependent nodes have the same set of actions. A cartel maintenance scheme [11] has closed-form optimal solutions for both cooperation and non-cooperation. A self-learning repeated game approach is proposed in [12] for individual distributed nodes to study the cooperation points and to develop protocols for maintaining them. Given the previous attention to the problem of nodes having mutual dependency, we will assume in this paper that the packet-forwarding problem of selfish nodes with mutual dependency

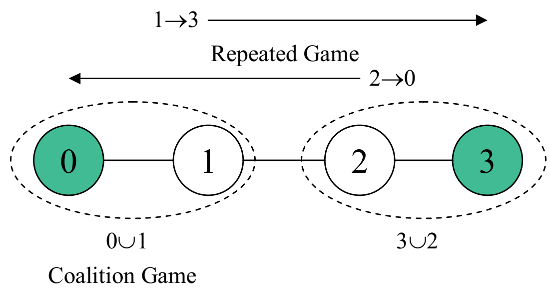

Fig. 1. Illustration example of the curse of boundary nodes.

has been solved and we will focus instead on the problems encountered by the boundary nodes.

B. *Curse of Boundary Nodes*

When there is no mutual dependency, the curse of boundary nodes occurs, an example of which is shown in Figure 1. Suppose node 1 needs to send data to node 3, and node 2 needs to send data to node 0. Because node 1 and node 2 depend on each other for packet-forwarding, they are obliged to do so because of the possible threat or retaliation from the other node. However, if node 0 wants to transmit to node 2 and node 3, or node 3 tries to communicate with node 0 and node 1, the nodes in the middle have no incentive to forward the packets due to their greediness. Moreover, this greediness cannot be punished in the future since the dependency is not mutual. This problem is especially severe for the nodes on the boundary of the network, so it is called *the curse of boundary nodes*.

On the other hand, if node 0 can form a coalition with node 1 and help node 1's transmission (for example to reduce the transmitted power of node 1), then node 1 has an incentive to help node 0 transmit as a reward. A similar situation arises for node 3 to form a coalition with node 2. We call nodes like 1 and 2 *backbone nodes*, while nodes like 0 and 3 are *boundary nodes*. In the following section, we will study how coalitions can be formed to address this issue using cooperative transmission.

III. Coalition Games with Cooperative Transmission

In this section, we first study a cooperative transmission technique that allows nodes to participate in coalitions. Then, we formulate a coalition game with cooperative transmission. Furthermore, we investigate the fairness issue and propose three types of fairness definitions. Finally, a protocol for packet-forwarding using repeated games and coalition games is constructed.

A. *Cooperative Transmission System Model*

First, we discuss the traditional direct transmission case. The source transmits its information to the destination with power P_d. The received SNR is

$$\Gamma_d = \frac{P_d |h_{s,d}|^2}{\sigma^2}, \tag{2}$$

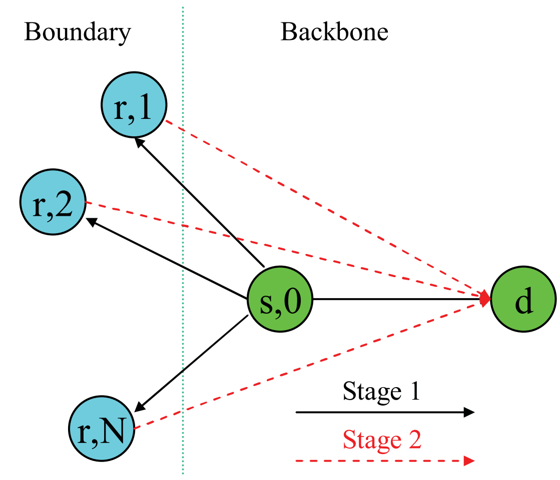

Fig. 2. Coalition game with cooperative transmission.

where $h_{s,d}$ is the channel response from the source to the destination and σ^2 is the noise level. To achieve the minimal link quality γ, we need for the transmitted power to be sufficiently large so that $\Gamma_d \geq \gamma$. The transmitted power is also upper bounded by P_{max}.

Next, we consider multiple nodes using the amplify-and-forward protocol [17][1] to transmit in two stages as shown in Figure 2. In stage one, the source node (denoted as node 0) transmits its information to the destination, and due to the broadcast nature of the wireless channels, the other nodes can receive the information. In stage two, the remaining N relay nodes help the source by amplifying the source signal. In both stages, the source and the relays transmit their signals through orthogonal channels using schemes like TDMA, FDMA, or orthogonal CDMA.

In stage one, the source transmits its information, and the received signals at the destination and the relays can be written respectively as

$$y_{s,d} = \sqrt{P_0} h_{s,d} x + n_{s,d}, \tag{3}$$

$$\text{and } y_{s,r_i} = \sqrt{P_0} h_{s,r_i} x + n_{s,r_i}, \forall i \in \{1, \ldots, N\}, \tag{4}$$

where P_0 is the transmitted power of the source, x is the transmitted symbol with unit power, h_{s,r_i} is the channel gain from the source to relay i, and $n_{s,d}$ and n_{s,r_i} are noise processes at the destination and relay, respectively. Without significant loss of generality, we assume that all noises have the same power σ^2.

In stage two, each relay amplifies the received signal from the source and retransmits it to the destination. The received signal at the destination for relay i can be written as

$$y_{r_i,d} = \frac{\sqrt{P_i}}{\sqrt{P_0 |h_{s,r_i}|^2 + \sigma^2}} h_{r_i,d} y_{s,r_i} + n_{r_i,d}, \tag{5}$$

where P_i is relay i's transmit power, $h_{r_i,d}$ is the channel gain from relay i to the destination, and $n_{r_i,d}$ is noise with variance σ^2.

[1]Other cooperative transmission protocols can be exploited in a similar way.

At the destination, the signal received at stage one and the N signals received at stage two are combined using maximal ratio combining (MRC). The SNR at the output of MRC is

$$\Gamma = \Gamma_0 + \sum_{i=1}^{N} \Gamma_i, \qquad (6)$$

where $\Gamma_0 = \frac{P_0|h_{s,d}|^2}{\sigma^2}$ and

$$\Gamma_i = \frac{P_0 P_i |h_{s,r_i}|^2 |h_{r_i,d}|^2}{\sigma^2(P_0|h_{s,r_i}|^2 + P_i|h_{r_i,d}|^2 + \sigma^2)}. \qquad (7)$$

On comparing (6) with (2), in order to achieve the desired link quality γ, we can see that the required power is always less than the direct transmission power, i.e., $P_0 < P_d$. So cooperation transmission can reduce the transmit power of the source node. This fact can give incentives of mutual benefits for the backbone nodes (acting as sources) and the boundary nodes (acting as relays), and consequently can cure the curse of the boundary nodes mentioned in Section II-B.

B. Coalition Game Formation for Boundary Nodes

In this subsection, we study possible coalitions between the boundary nodes and the backbone nodes, for situations in which the boundary nodes can help relay the information of the backbone nodes using cooperative transmission. In the following, we first define some basic concepts that will be needed in our analysis.

Definition 2: A *coalition* S is defined to be a subset of the total set of nodes $\mathbb{N} = \{0, \ldots, N\}$. The nodes in a coalition want to cooperate with each other. The *coalition form* of a game is given by the pair $(\mathbb{N}, v)$, where v is a real-valued function, called the *characteristic function*. $v(S)$ is the value of the cooperation for coalition S with the following properties:

1) $v(\emptyset) = 0$.
2) Super-additivity: if S and Z are disjoint coalitions ($S \bigcap Z = \emptyset$), then $v(S) + v(Z) \le v(S \bigcup Z)$.

The coalition states the benefit obtained from cooperation agreements. But we still need to examine whether or not the nodes are willing to participate in the coalition. A coalition is called *stable* if no other coalition will have the incentive and power to upset the cooperative agreement. Such division of v is called a point in the *core*, which is defined by the following definitions.

Definition 3: A payoff vector $\mathbf{U} = (U_0, \ldots, U_N)$ is said to be *group rational* or *efficient* if $\sum_{i=0}^{N} U_i = v(\mathbb{N})$. A payoff vector $\mathbf{U}$ is said to be *individually rational* if the node can obtain the benefit no less than acting alone, i.e. $U_i \ge v(\{i\}),\ \forall i$. An *imputation* is a payoff vector satisfying the above two conditions.

Definition 4: An imputation $\mathbf{U}$ is said to be unstable through a coalition S if $v(S) > \sum_{i \in S} U_i$, i.e., the nodes have incentive for coalition S and upset the proposed $\mathbf{U}$. The set C of a stable imputation is called the *core*, i.e.,

$$C = \{\mathbf{U} : \sum_{i \in \mathbb{N}} U_i = v(\mathbb{N}) \text{ and } \sum_{i \in S} U_i \ge v(S),\ \forall S \subset \mathbb{N}\}. \qquad (8)$$

In the economics literature, the core gives a reasonable set of possible shares. A combination of shares is in the core if there is no sub-coalition in which its members may gain a higher total outcome than the combination of shares of concern. If a share is not in the core, some members may be frustrated and may think of leaving the whole group with some other members and form a smaller group.

In the packet-forwarding network as shown in Figure 2, we first assume one backbone node to be the source node (node 0) and the nearby boundary nodes (node 1 to node N) to be the relay nodes. We will discuss the case of multiple source nodes later. If no cooperative transmission is employed, the utilities for the source node and the relay nodes are

$$v(\{0\}) = -P_d, \text{ and } v(\{i\}) = -\infty, \forall i = 1, \ldots, N. \qquad (9)$$

Here a utility of $-\infty$ means that even though a boundary user tries to use maximal power for transmission, it cannot successfully deliver any packets due to the curse.

With cooperative transmission and a grand coalition that includes all nodes, the utilities for the source node and the relay nodes are

$$U_0 = -P_0 - \sum_{i=1}^{N} \alpha_i P_d \qquad (10)$$

$$\text{and } U_i = -\frac{P_i}{\alpha_i}, \qquad (11)$$

where α_i is the ratio of the number of packets that the backbone node is willing to forward for boundary node i, to the number of packets that the boundary node i relays for the backbone node using cooperative transmission. Smaller α_i means the boundary nodes have to relay more packets before realizing the rewards of packet forwarding. The other interpretation of the utility is as the average power per transmission for the boundary nodes[2]. The following theorem gives conditions under which the core is not empty, i.e, in which the grand coalition is stable.

Theorem 2: The core is not empty if $\alpha_i \ge 0,\ i = 1, \ldots, N$, and α_i are such that $U_0 \ge v(\{0\})$, i.e,

$$\sum_{i=1}^{N} \alpha_i \le \frac{P_d - P_0}{P_d}. \qquad (12)$$

Proof: First, any relay node will get $-\infty$ utility if it leaves the coalition with the source node, so no node has incentive to leave the coalition with node 0. Then, from (6), the inclusion of relay nodes will increase the received SNR monotonically. So P_0 will decrease monotonically with the addition of any relay node. As a result, the source node has an incentive to include all the relay nodes, as long as the source power can be reduced, i.e., $U_0 \ge v(\{0\})$. A grand coalition is formed and the core is not empty if (12) holds. ■

The concept of the core defines the stability of a utility allocation. However, it does not define how to allocate the utility. For the proposed game, each relay node can obtain different utilities by using different values of α_i. In the next three subsections, we study how to achieve min-max fairness, average fairness, and market fairness.

[2]Notice that we omit the transmitted power needed to send the boundary node's own packet to the backbone node, since it is irrelevant to the coalition.

C. Min-Max Fairness of a Game Coalition using Nucleolus

We introduce the concepts of *excess*, *kernel*, and *nucleolus* [1], [2]. For a fixed characteristic function v, an imputation $\mathbf{U}$ is found such that, for each coalition S and its associated dissatisfaction, an optimal imputation is calculated to minimize the maximum dissatisfaction. The dissatisfaction is quantified as follows.

Definition 5: The measure of dissatisfaction of an imputation $\mathbf{U}$ for a coalition S is defined as the *excess*:

$$e(\mathbf{U}, S) = v(S) - \sum_{j \in S} U_j. \quad (13)$$

Obviously, any imputation $\mathbf{U}$ is in the core, if and only if all its excesses are negative or zero.

Definition 6: A *kernel* of v is the set of all allocations $\mathbf{U}$ such that

$$\max_{S \subseteq \mathbb{N}-j, i \in S} e(\mathbf{U}, S) = \max_{T \subseteq \mathbb{N}-i, j \in T} e(\mathbf{U}, T). \quad (14)$$

If nodes i and j are in the same coalition, then the highest excess that i can make in a coalition without j is equal to the highest excess that j can make in a coalition without i.

Definition 7: The *nucleolus* of a game is the allocation $\mathbf{U}$ that minimizes the maximum excess:

$$\mathbf{U} = \arg \min_{\mathbf{U}} (\max \ e(\mathbf{U}, S), \ \forall S). \quad (15)$$

The nucleolus of a game has the following property: The nucleolus of a game in coalitional form exists and is unique. The nucleolus is group rational and individually rational. If the core is not empty, the nucleolus is in the core and kernel. In other word, the nucleolus is the best allocation under the min-max criterion.

Using the above concepts, we prove the following theorem to show the optimal α_i in (10) to have min-max fairness.

Theorem 3: The maximal α_i to yield the nucleolus of the proposed coalition game is given by

$$\alpha_i = \frac{P_d - P_0(\mathbb{N})}{N P_d}, \quad (16)$$

where $P_0(\mathbb{N})$ is the required transmitted power of the source when all relays transmit with transmitted power P_{max}.

Proof: Since for any coalition other than the grand coalition, the excess will be $-\infty$, we need only consider the grand coalition. Suppose the min-max utility is μ for all nodes, i.e.

$$\mu = -\frac{P_i}{\alpha_i}. \quad (17)$$

From (12) and since U_i is monotonically increasing with α_i in (11), we have

$$\alpha_i = \frac{P_i}{\sum_{i=1}^{N} P_i} \cdot \frac{(P_d - P_0)}{P_d}. \quad (18)$$

Since P_0 in (6) is a monotonically increasing function of P_i, to achieve the maximal α_i and μ, each relay transmits with the largest possible power P_{max}. Notice here we assume the backbone node can accept arbitrarily small power gain to join the coalition. ■

D. Average Fairness of Game Coalition using the Shapley Function

The core concept defines the stability of an allocation of payoff and the nucleolus concept quantifies the min-max fairness of a game coalition. In this subsection, we study another average measure of fairness for each individual using the concept of a Shapley function [1], [2].

Definition 8: A *Shapley function* ϕ is a function that assigns to each possible characteristic function v a vector of real numbers, i.e.,

$$\phi(v) = (\phi_0(v), \phi_1(v), \phi_2(v), \ldots, \phi_N(v)) \quad (19)$$

where $\phi_i(v)$ represents the worth or value of node i in the game. There are four Shapley Axioms that $\phi(v)$ must satisfy

1) *Efficiency Axiom*: $\sum_{i \in \mathbb{N}} \phi_i(v) = v(\mathbb{N})$.
2) *Symmetry Axiom*: If node i and node j are such that $v(S \bigcup \{i\}) = v(S \bigcup \{j\})$ for every coalition S not containing node i and node j, then $\phi_i(v) = \phi_j(v)$.
3) *Dummy Axiom*: If node i is such that $v(S) = v(S \bigcup \{i\})$ for every coalition S not containing i, then $\phi_i(v) = 0$.
4) *Additivity Axiom*: If u and v are characteristic functions, then $\phi(u + v) = \phi(v + u) = \phi(u) + \phi(v)$.

It can be proved that there exists a unique function ϕ satisfying the Shapley axioms. Moreover, the Shapley function can be calculated as

$$\phi_i(v) = \sum_{S \subset \mathbb{N}-i} \frac{(|S|)!(N - |S|)!}{(N+1)!} [v(S \cup \{i\}) - v(S)]. \quad (20)$$

Here $|S|$ denotes the size of set S and $\mathbb{N} = \{0, 1, \ldots N\}$.

The physical meaning of the Shapley function can be interpreted as follows. Suppose one backbone node plus N boundary nodes form a coalition. The nodes join the coalition in random order. So there are $(N+1)!$ different ways that the nodes might be ordered in joining the coalition. For any set S that does not contain node i, there are $|S|!(N - |S|)!$ different ways to order the nodes so that S is the set of nodes that enter the coalition before node i. Thus, if the various orderings are equally likely, $|S|!(N - |S|)!/(N+1)!$ is the probability that, when node i enters the coalition, the coalition of S is already formed. When node i finds S ahead of it as it joins the coalition, then its marginal contribution to the worth of the coalition is $v(S \cup \{i\}) - v(S)$. Thus, under the assumption of randomly-ordered joining, the Shapley function of each node is its expected marginal contribution when it joins the coalition.

In our specific case, we consider the case in which the backbone node is always in the coalition, and the boundary nodes randomly join the coalition. We have $v(\{0\}) = -P_d$ and

$$v(\mathbb{N}) = P_d - P_0(\mathbb{N}) - \sum_{i \in \mathbb{N}} \alpha_i P_d, \quad (21)$$

which is the overall power saving. The problem here is how to find a given node's α_i that satisfies the average fairness, which is addressed by the following theorem.

Theorem 4: The maximal α_i that satisfies the average fairness with the physical meaning of the Shapley function is given by

$$\alpha_i = \frac{P_i^s}{P_d}, \quad (22)$$

where P_i^s is the average power saving with random entering orders, which is defined as

$$P_i^s = \frac{1}{N}[P_d - P_0(\{i\})] + \frac{\sum_{j=1,j\neq i}^{N}[P_0(\{j\}) - P_0(\{i,j\})]}{N(N-1)} + \cdots . \quad (23)$$

Proof: The maximal α_i is solved by the following equations:

$$\begin{cases} \frac{\alpha_i}{\alpha_j} = \frac{\phi_i}{\phi_j}, \\ v(\mathbb{N}) \geq 0. \end{cases} \quad (24)$$

The first equation in (24) is the average fairness according to the Shapley function, and the second equation in (24) is the condition for a non-empty core. Similar to min-max fairness, we assume that the backbone node can accept arbitrarily small power gain to join the coalition.

If boundary node i is the first to join the coalition, the marginal contribution for power saving is $\frac{1}{N}[P_d - P_0(\{i\}) - \alpha_i P_d]$, where $\frac{1}{N}$ is the probability. If boundary node i is the second to join the coalition, the marginal contribution is $\frac{\sum_{j=1,j\neq i}^{N}[P_0(\{j\})+\alpha_j P_d - P_0(\{i,j\})-(\alpha_i+\alpha_j)P_d]}{N(N-1)}$. By means of some simple derivations, we can obtain the Shapley function ϕ_i as

$$\phi_i = -\alpha_i P_d + \frac{1}{N}[P_d - P_0(\{i\})] + \frac{\sum_{j=1,j\neq i}^{N}[P_0(\{j\}) - P_0(\{i,j\})]}{N(N-1)} + \cdots , \quad (25)$$

and then we can obtain

$$\alpha_i = \frac{[P_d - P_0(\mathbb{N})]P_i^s}{P_d \sum_{j=1}^{N} P_j^s}. \quad (26)$$

Since

$$P_d - P_0(\mathbb{N}) = \sum_{j=1}^{N} P_j^s, \quad (27)$$

we prove (22). ■

Notice that different nodes have different values of P_i^s, due to their channel conditions and abilities to reduce the backbone node's power. Compared with the min-max fairness in the previous subsection, the average fairness using the Shapley function gives different nodes different values of α_i according to their locations.

E. Market Fairness of Game Coalition with Multiple Backbone Nodes

In the previous two subsections, we have discussed two types of fairness with one backbone node and multiple boundary nodes. However, since the boundary nodes depend entirely on the backbone node for packet forwarding, the backbone node can disregard the fairness and coerce the boundary nodes by asking for an arbitrary amount of payoff before helping the boundary nodes send their packets. The backbone node can join the coalition only if $v(\mathbb{N}) > v_0$, where v_0 is a positive value. So the α_i in (16) and (22) becomes

$$\alpha_i = \begin{cases} \frac{P_d - P_0(\mathbb{N}) - v_0}{N P_d}, & \text{min-max fairness} \\ \frac{[P_d - P_0(\mathbb{N}) - v_0]P_i^s}{P_d[P_d - P_0(\mathbb{N})]}, & \text{average fairness.} \end{cases} \quad (28)$$

Thus, a greedy backbone node can increase v_0 sufficiently large so that the boundary nodes receive arbitrarily small α_i. This means that the backbone node can arbitrarily impose on the boundary nodes for relaying and almost never give rewards in return. The underlying reason for this is because the backbone node has no competition from other nodes. In economic networks, this phenomena is called "monopoly" and the consumer suffers a minimal quality of services as a result.

To solve this problem, we discuss the case in which there are multiple backbone nodes, which is similar to "antitrust" in economic networks. First, we prove the following theorem for the core with multiple backbone nodes.

Theorem 5: If the number of backbone nodes is greater than 1, the core is surely empty.

Proof: Suppose there are M backbone nodes. There is no mutual benefit between these backbone nodes to form coalitions using cooperative transmission. The boundary nodes join the coalitions that give them the highest payoff, i.e., they seek coalitions that allow them to relay the fewest packets before a reward for packet forwarding is given. So the grand coalition is divided into M coalitions, since there are benefits for a subset of nodes to form the new coalition instead of joining the grand coalition. As a result, the core is surely empty when $M \geq 2$. ■

Since the grand coalition does not exist and the boundary nodes can select the backbone nodes with which to form coalitions, it is to the backbones nodes' benefits to adjust the packet-forwarding policy to attract more boundary nodes to reduce the transmitted power. So competition among the backbone nodes is introduced. Here we denote α_i^m as the m^{th} backbone node's packet-forwarding policy for the i^{th} boundary node, and denote the nodes' coalition partition matrix as

$$\mathbf{A}_{im} = \begin{cases} 1, & \text{if boundary node } i \text{ joins coalition with backbone node } m, \\ 0, & \text{otherwise.} \end{cases} \quad (29)$$

Boundary node i selects the smallest α_i^m and joins the corresponding coalition with backbone node m. The optimal utility is obtained when the packets are relayed only by this backbone node. So we have

$$\sum_{m=1}^{M} \mathbf{A}_{im} = 1, \mathbf{A}_{im} \in \{0,1\}, \forall i, m. \quad (30)$$

For each backbone node, the optimization is to adjust its policy α_i^m so that the overall power saving is largest. We can write the utility for the m^{th} backbone node as

$$U_0^m = \max_{\alpha_i^m, \forall i} (-P_0^m - \sum_{i=1}^{N} \alpha_i^m \mathbf{A}_{im} P_d), \quad (31)$$

where P_0^m is the reduced transmitted power using cooperative transmission.

For each boundary node, the optimization is to select the backbone node to join the coalition. The problem can be written as

$$U_i = \max_{\mathbf{A}_{im}, \forall m} -\frac{P_i}{\sum_{m=1}^{M} \mathbf{A}_{im} \alpha_i^m} \quad (32)$$

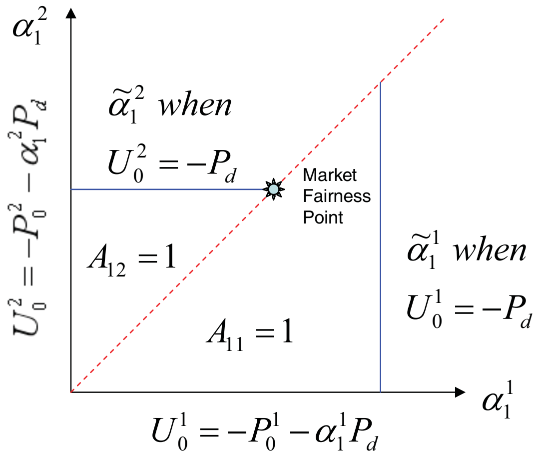

Fig. 3. Market fairness point for a two-backbone-node one-boundary-node example.

$$\text{s.t.} \sum_{m=1}^{M} \mathbf{A}_{im} = 1, \mathbf{A}_{im} \in \{0,1\}, \forall m.$$

In order for a backbone node to win the coalition with a boundary node, the backbone node has to set the lowest α_i^m among all the backbone nodes. On the other hand, different boundary nodes have different abilities to reduce different backbone nodes' power. Using these facts, we define a new type of fairness as follows.

Definition 9: Market fairness achieves the equilibrium of the two-level games in (31) and (32). In this type of fairness, no backbone node can set its policy α_i^m lower to get a higher utility if the other backbone nodes do not change their policies. On the other hand, it is in the boundary nodes' best interest to join the coalitions under this market fairness.

In Figure 3, we show an example of market fairness for a two-backbone-node and one-boundary-node example. The x-axis and y-axis are the two backbone nodes' policies α_1^1 and α_1^2, respectively. Below the 45 degree line, $\alpha_1^1 < \alpha_1^2$. As a result, the boundary node joins the coalition with backbone node 1, i.e., $\mathbf{A}_{11} = 1$ and $\mathbf{A}_{12} = 0$. Otherwise, the boundary node forms a coalition with backbone node 2, i.e., $\mathbf{A}_{11} = 0$ and $\mathbf{A}_{12} = 1$. From (11), the utility is a linear function of the policy $\alpha_1^m,\ m = 1, 2$. For a backbone node, the minimal requirement for joining the coalition is that its power is less than the direct transmission power. In Figure 3, we show the $\tilde{\alpha}_1^m$ for $U_0^m = -P_d, m = 1, 2$. Since different boundary nodes can help reduce the backbone nodes' transmission power P_0^m differently, different values of $\tilde{\alpha}_1^m$ are required to achieve $U_0^m = -P_d$. In our case, backbone node 1 is the winner by providing $\alpha_1^1 = \tilde{\alpha}_1^2$ and its utility gain is $P_d - P_0^1 - \tilde{\alpha}_1^2 P_d$. Notice that backbone node 1 cannot let $\alpha_1^1 < \tilde{\alpha}_1^2$, since backbone node 2 then has the ability to give lower α_1^2 to attract the boundary node. On the other hand, as long as $\alpha_1^1 > \tilde{\alpha}_1^2$, backbone node 1 has no incentive to increase α_1^1. From this example, we can see that the backbone nodes have to offer high enough α_i^m to form coalitions with the boundary nodes, because of the competition with other backbone nodes.

Notice that the cooperative transmission power P_0^m depends on which boundary nodes join the coalition, i.e., P_0^m is a function of vector $[\mathbf{A}_{1m}, \ldots, \mathbf{A}_{Nm}]$. In order to find the point with market fairness, we formulate the following programming method.

$$\min_{P_0^m, \alpha_i^m > 0, \forall i, m} \sum_{m=1}^{M} \left(P_0^m(\mathbf{A}_{1m}, \ldots, \mathbf{A}_{Nm}) + \sum_{i=1}^{N} \alpha_i^m \mathbf{A}_{im} P_d \right) \tag{33}$$

$$\text{s.t.} \begin{cases} \forall i, \mathbf{A}_{im} = 1, \text{ if } \alpha_i^m > \alpha_i^{m'} \text{ and } \forall m' \neq m; \\ \quad \mathbf{A}_{im} = 0, \text{ otherwise}, \\ \forall m, P_0^m(\mathbf{A}_{1m}, \ldots \mathbf{A}_{Nm}) + \sum_{i=1}^{N} \alpha_i^m \mathbf{A}_{im} P_d \le P_d. \end{cases}$$

Here the first constraint is *Boundary Node Rationality*, which means the boundary node will select the optimal α_i^m. The second constraint is *Backbone Node Rationality*, which states that the backbone nodes will only join a coalition if their power can be reduced by doing so. The objective function captures the phenomenon that the backbone nodes will maximize their utilities by reducing α_i^m as much as possible. The problem in (33) can be efficiently solved by algorithms such as the *cutting-plane* and *simplex* algorithms [28], [29]. The problem can be solved by either the backbone node or the boundary node, since the outcome can benefit both nodes.

F. Joint Repeated-Game and Coalition-Game Packet-Forwarding Protocol

Using the above analysis, we now develop a packet-forwarding protocol based on repeated games and coalition games having on the following steps.

Packet-Forwarding Protocol using Repeated Games and Coalition Games

1) Route discovery for all nodes.
2) Packet-Forwarding enforcement for the backbone nodes, using threat of future punishment in the repeated games.
3) Neighbor discovery for the boundary nodes.
4) Coalition game formation.
5) Packet relay for the backbone nodes with cooperative transmission.
6) Transmission of the boundary nodes' own packets to the backbone nodes for forwarding.

First, all nodes in the network undergo route discovery. Then each node knows who depends on it and on whom it depends for transmission. Using this route information, the repeated games can be formulated for the backbone nodes. The backbone nodes forward the other nodes' information because of the threat of future punishment if these packets are not forwarded. Due to the network topology, some nodes' transmissions depend on the others while the others do not depend on these nodes. These nodes are most often located at the boundary of the network. In the next step, these boundary nodes try to find their neighboring backbone nodes. Then, the boundary nodes try to form coalitions with the backbone nodes, so that the boundary nodes can be rewarded for transmitting their own packets. Cooperative transmission gives an opportunity for the boundary nodes to pay some "credits" first to the backbone nodes for the rewards of packet-forwarding in return. On the other hand, competition among the backbone nodes prevents the boundary nodes from being forced to accept the minimal payoffs.

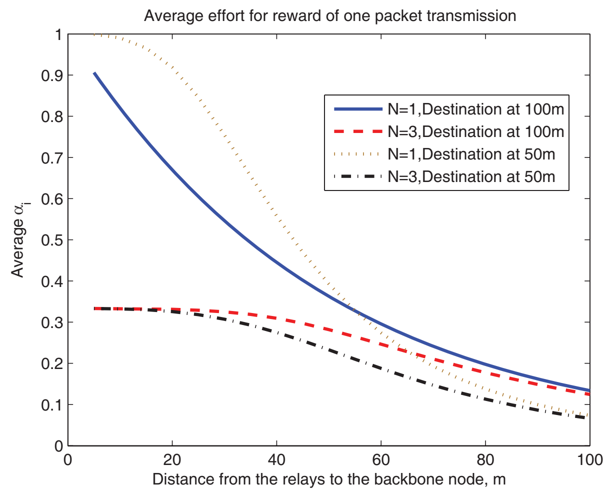

Fig. 4. α for different channels and no. of nodes, min-max fairness.

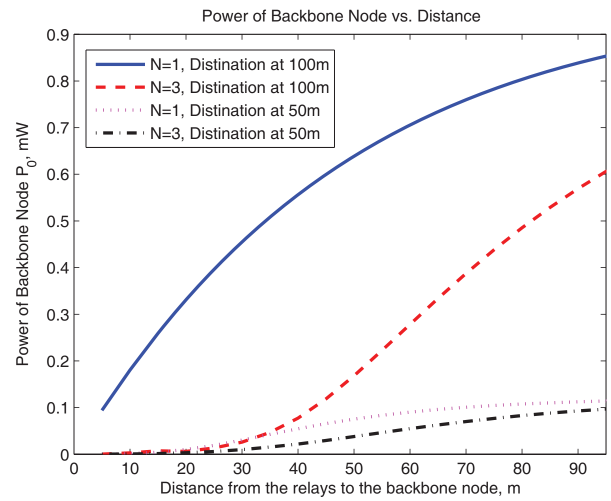

Fig. 5. P_0 for different channels and no. of nodes, min-max fairness.

It is worth mentioning the following point regarding energy efficiency. From the overall system point of view, it is not energy efficient for the backbone nodes to depend on the boundary nodes for cooperation, since the boundary nodes are further away from the backbones' destination. If a centralized control system is enforced, it is energy efficient for the backbone nodes to forward the packets of the boundary nodes. However, if distributed and greedy users are considered, the curse happens. Our approach provides the incentives for the backbone nodes to help the boundary nodes, so that the curse is relieved. But this comes with a cost, in the sense that the boundary nodes have to help the backbone nodes in an energy-inefficient way. Nevertheless, this is already much better than the totally accursed situation in which no packet of the boundary nodes can be transmitted.

Another implementation concern arises from node mobility. The proposed algorithm is similar to a contract. As long as the boundary nodes help the transmission and the backbone nodes help the packet forwarding, the contract is fulfilled. This can happen with transmission of $1 + \frac{1}{\alpha}$ packets. If mobility is considered, the new contract needs to be calculated to accounts for the new positions of the nodes. As long as the speed of fulfilling the contract is relatively larger than the speed of channel changing, the proposed scheme can be implemented without major modification. Nevertheless, if the channel changes too rapidly, some stochastic models can be used to estimate the expected payoff (utility). Then the rest of the analysis can be applied in a very similar way.

IV. Simulation Results

We model all channels as additive white Gaussian noise channels having the exponent of propagation loss as 3; that is, power falls off spatially according to an inverse-cubic law. The maximal transmitted power is 10dbm and the noise level is - 60dbm. The minimal SNR γ is 10dB. In the first setup, we assume the backbone node is located at $(0m, 0m)$, and the destination is located at either $(100m, 0m)$ or $(50m, 0m)$. The boundary nodes are located on an arc with angles randomly distributed from 0.5π to 1.5π and with distances varying from 5m to 100m.

In Figure 4, we study the min-max fairness and show the average α_i over 1000 iterations as a function of distance from the relays to the source node. Due to the min-max nature, all boundary nodes have the same α_i. When the distance is small, i.e., when the relays are located close to the source, α_i approaches $\frac{1}{N}$. This is because the relays can serve as a virtual antenna for the source, and the source needs very low power for transmission to the relays. When the distance is large, the relays are less effective and α_i decreases, which means that the relays must transmit more packets for the source to earn the rewards of packet-forwarding. When the destination is located at 50m, the source-destination channel is better than that at $100m$. When $N = 1$ and the source-destination distance is 50m, the relays close to the source have larger values of α_i and the relays farther away have lower values of α_i than that in the 100m case. In Figure 5, we show the corresponding P_0 for the backbone node. We can see that P_0 increases when the distances between the boundary nodes to the backbone node increase.

If we consider the multiple backbone (multiple core) case with min-max fairness, Figure 4 and Figure 5 provide the boundary nodes a guideline for selecting a backbone node with which to form a coalition. First, a less crowded coalition is preferred. Second, the nearest backbone node is preferred. Third, for $N = 1$, if the source-destination channel is good, the closer backbone node is preferred; otherwise, the farther one can provide larger α_i.

Next, we investigate the average fairness using the Shapley function. The simulation setup is as follows. The backbone node is located at $(0m, 0m)$ and the destination is located at $(-50m, 0m)$. Boundary node 1 is located at $(20m, 0m)$ or $(50m, 0m)$. Boundary node 2 moves from $(5m, 0m)$ to $(100m, 0m)$. The remaining simulation parameters are the same. In Figure 6, we show maximal α_i for two boundary nodes. We can see that when boundary node 2 is closer to the backbone node than boundary node 1, $\alpha_2 > \alpha_1$, i.e., boundary node 2 can help relay fewer packets for backbone node 1 before being rewarded. The two curves for α_1 and α_2 for the same boundary node 1 location cross at the boundary node 1 location. The figure shows that the average fairness using

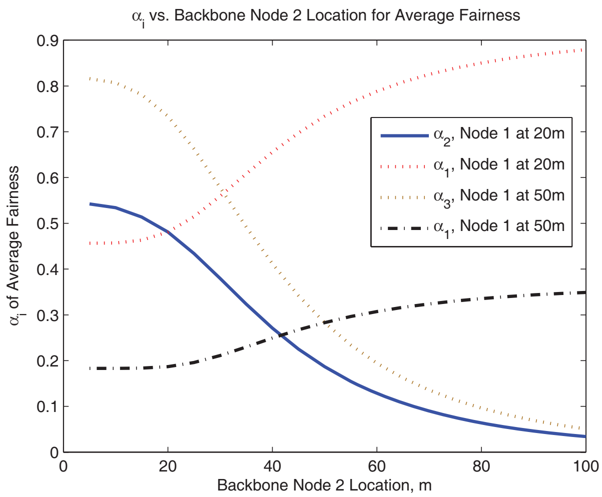

Fig. 6. α_i of average fairness for different users' locations.

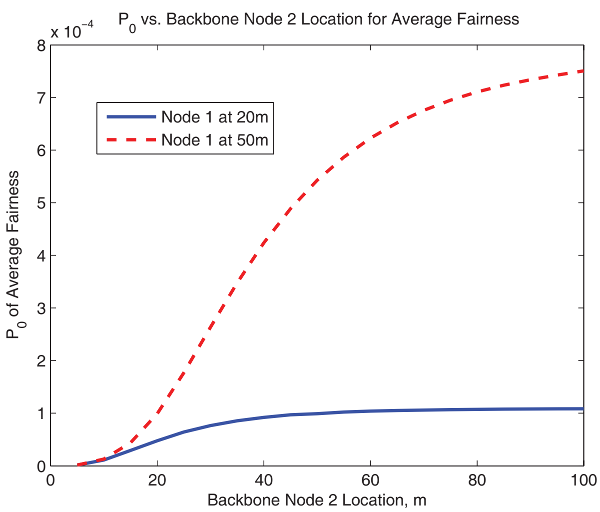

Fig. 7. P_0 of average fairness for different users' locations.

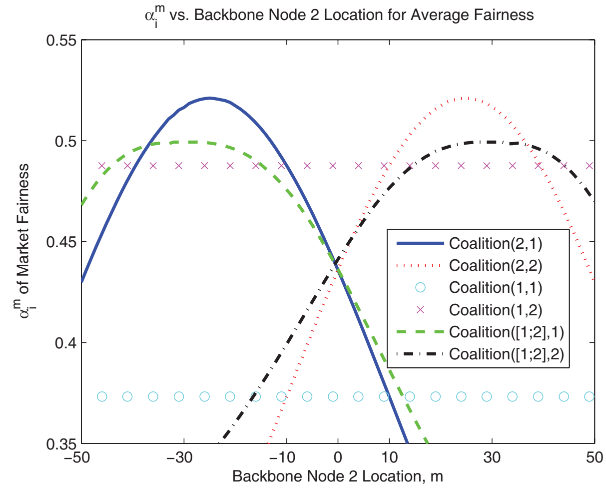

Fig. 8. α_i^m of market fairness for different users' locations.

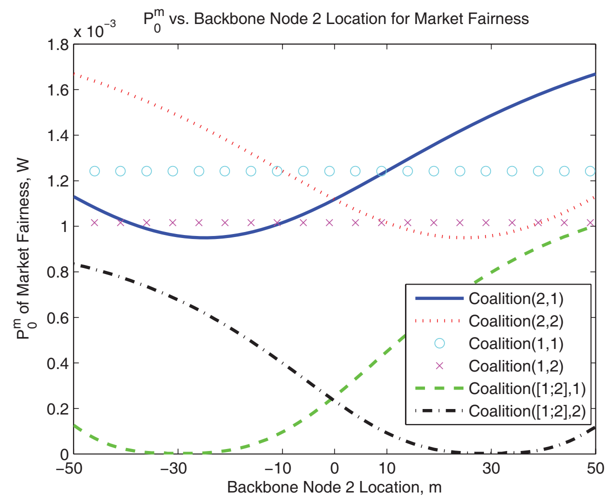

Fig. 9. P_0^m of market fairness for different users' locations.

the Shapley function gives greater rewards to the boundary node whose channel is better and who can help the backbone node more. When boundary node 2 moves from $(20m, 0m)$ to $(50m, 0m)$, α_1 becomes smaller, but α_2 becomes larger. This is because the backbone node must depend on boundary node 2 more for relaying. However, the backbone node will pay less for the boundary nodes. Notice that α_i at the crossover point is lower. This is because the overall power for the backbone node is high when boundary node 2 is far away, as shown in Figure 7.

Further, we study market fairness with the following setup. Backbone node 1 and backbone node 2 are located at $(0m, -30m)$ and $(0m, 30m)$, respectively. The destination is located at $(-50m, 0m)$ and boundary node 1 is located at $(44m, 10m)$. Boundary node 2 moves from $(44m, -50m)$ to $(44m, 50m)$. The remaining simulation parameters are the same as before. In Figure 8 and Figure 9, we show α_i^m and P_0^m, respectively, under six different scenarios:

1) (2,1): Coalition of boundary node 2 with backbone node 1;
2) (2,2): Coalition of boundary node 2 with backbone node 2;
3) (1,1): Coalition of boundary node 1 with backbone node 1;
4) (1,2): Coalition of boundary node 1 with backbone node 2;
5) ([1;2],1): Coalition of both boundary nodes with backbone node 1;
6) ([1;2],2): Coalition of both boundary nodes with backbone node 2.

Since boundary node 1 is not moving, coalition (1,1) and coalition (1,2) are horizontal lines. From the curves in Figure 8, we can see that a boundary node prefers to form a coalition with the closest backbone node, and vice versa. However, due to competition from the other nodes, the coalition formation is affected by combinations of many factors which are analyzed as follows.

When boundary node 2 moves, there are seven possible scenarios for forming different coalitions in Table I. From Figure 8 and Table I, we can see that rational boundary node i selects the largest α_i^m and joins the corresponding coalition with backbone node m. Sometime, it is to both boundary nodes' benefit to form a coalition with one of the

TABLE I
MARKET FAIRNESS COALITIONS

Case	Coalition (optimal for boundary node)	Minimal α offered by backbone node
I	(1,2),(2,1)	α_1^1, α_2^2
II	([1;2],1)	α_1^2, α_2^2
III	(2,1),(1,2)	α_1^1, α_2^2
IV	(1,2),(2,1)	α_1^1, α_2^2
V	(2,2),(1,1)	α_1^2, α_2^1
VI	([1;2],2)	α_1^1, α_2^1
VII	(1,2),(2,1)	α_1^1, α_2^2

backbone nodes as in case II and case VI. However, because the backbone nodes are greedy, the boundary nodes can obtain only slightly better rewards than the opponent's offer. For example, in case I, boundary node 1 prefers backbone node 2. But as long as the backbone node gives an offer better than α_1^1, boundary node 1 must accept the offer. On the other hand, from Figure 9, the backbone nodes want to form coalitions with both boundary nodes so as to have the minimal transmitted power. But because of competition from other backbone nodes and rationality of the boundary nodes, the backbone nodes must form a coalition with only one boundary node or sometime not at all. The above facts demonstrate the reason why the proposed market fairness can effectively counteract the greediness of the backbone nodes.

Next, we set up a linear network with 50 nodes spread evenly along a line. The distance between nodes is 100m. The users are indexed as user 1 to user 50 from one end to the other. Each user transmits to any other user with equal probability. In Figure 10, we show the probability that a node can be a boundary node as a function of the user index. We show two cases with one destination and five destinations for each user, respectively. We can see that the nodes in the middle of the network have lower probabilities to become boundary nodes, as one would expect. As a result, α for those nodes is large, which means those nodes take less on average to help the others' transmission, because of their locations. For the five destination case, each user transmits to five different destination nodes, and as a result depends more on the other nodes. So the nodes in the middle have much lower probability to be boundary nodes than in the one-destination case.

Finally, we examine the degree to which the coalition game can improve the network connectivity. Here we define the network connectivity as the probability that a randomly located node can connect to the other nodes. All nodes are randomly located within a square of size $B \times B$. In Figure 11, we show the network un-connectivity as a function of B for the numbers of nodes equal to 100 and 500. With increasing network size, the node density becomes lower, and more and more nodes are located at the boundary and must depend on the others for packet-forwarding. If no coalition game is formed, these boundary nodes cannot transmit their packets due to the selfishness of the other nodes. With the coalition game, the network connectivity can be improved by about 50%. The only chance that a node cannot connect to the other nodes is when this node is located too far away from any other node. Thus, we can seen by this example that the coalition game can cure the curse of the boundary nodes in wireless packet-forwarding networks with selfish nodes.

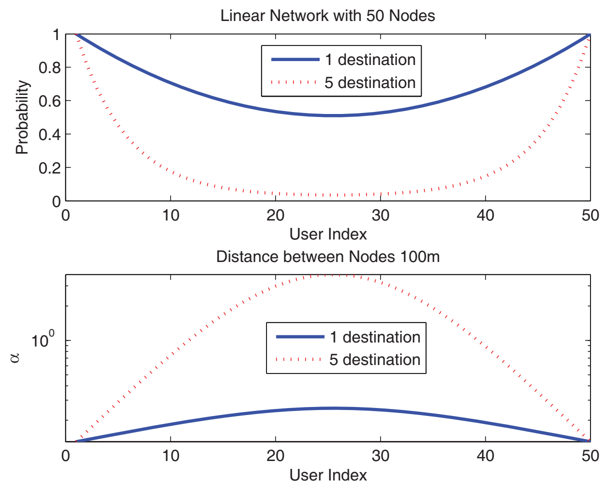

Fig. 10. Linear network setup.

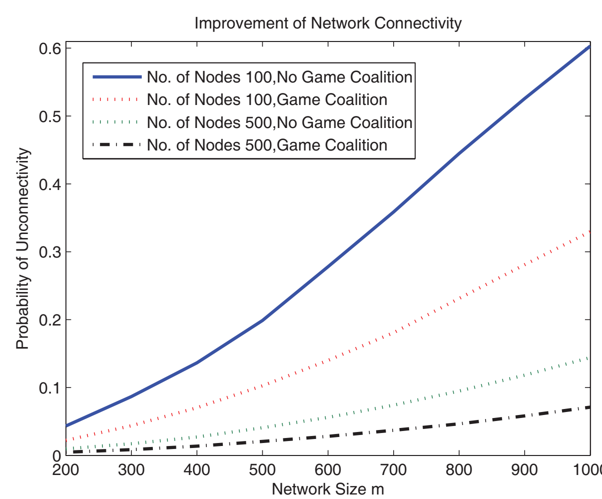

Fig. 11. Network connectivity vs. network size.

V. CONCLUSIONS

In this paper, we have proposed a coalition game approach to provide incentives to selfish nodes in wireless packet-forwarding networks using cooperative transmission, so that the boundary nodes can transmit their packets effectively. We have used the concepts of coalition games to maintain stable and fair game coalitions. Specifically, we have studied three fairness concepts: min-max fairness, average fairness, and market fairness. The market fairness uses competition among nodes to effectively counteract the greediness of the backbone nodes. A protocol has been constructed using repeated games and coalition games. From simulation results, we have seen how boundary nodes and backbone nodes form coalitions according to different fairness criteria. We have also seen by example that network connectivity can be improved by about 50%, compared to the pure repeated game approach.

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