Cooperative Strategy by Stackelberg Games under Energy Constraint in Multi-hop Relay Networks

Hyukjoon Kwon, HyungJune Lee, and John M. Cioffi
Electrical Engineering, Stanford University, Stanford, CA 94305
Email: {hjkwon, abbado, cioffi}@stanford.edu

***Abstract*— This paper presents a cooperative relay strategy with a game-theoretic perspective. In multi-hop networks, each node needs to send traffic via relay nodes, which behave independently while staying aware of energy constraints. To encourage a relay to forward the packets, the proposed scheme formulates a Stackelberg game where two nodes sequentially bid their willingness weights to cooperate for their own benefits. Accordingly, all the nodes are encouraged to be cooperative only if a sender is cooperative and alternatively to be non-cooperative only if a sender is non-cooperative. This selective strategy changes the reputations of nodes depending on the amount of their bidding at each game and motivates them to maintain a good reputation so that all their respective packets can be treated well by other relays. This paper analyzes a Nash equilibrium from the proposed scheme and validates a sequential-move game by Stackelberg competition as opposed to a simultaneous-move game by Cournot competition. Simulation results demonstrate that the proposed scheme turns non-cooperative nodes into cooperative nodes and increases the cooperative relaying stimulus all over the nodes. Thus, every node forwards other packets with higher probability, thereby achieving a higher overall payoff.**

I. Introduction

Recently, multi-hop networks where each node operates independently without any centralized base stations have been widely investigated. This network can use cooperation among nodes so as to increase the total throughput further than a single-hop network [1]. However, each node is autonomous and selfish in nature, and thus, spontaneous cooperation among nodes is challenged. To accommodate this nature of multi-hop networks, many approaches to stimulate cooperation have been proposed. These approaches are roughly classified into incentive-based schemes and pricing-based schemes.

In incentive-based schemes, nodes are rewarded for appropriate behaviors such as being cooperative, or punished for inappropriate behaviors such as being selfish. Depending on the types of incentive, these schemes are divided into reputation-based models and market-based (or payment-based) models. In reputation-based models, every node observes nearby neighbors to detect whether they forward data packets or not, for example, by using a watchdog mechanism [2]. When a node has been deliberately dropping others' packets, the nearby nodes evaluate the node as a non-cooperative node, and isolate it from their route selection [3]. To increase the credibility for a node, [4] evaluates a node with a weighted combination of three different reputations: subjective, indirect, and functional reputations. These reputation-based models are analytically studied based on Bayesian games in [5] and on the tit-for-tat strategy in [6]. However, these approaches assume that none of the nodes exhibit any misbehavior. For example, if a malicious node accuses well-behaved relays of non-cooperative nodes, they would be isolated and the whole system would operate in error.

The market-based models use payments as incentives for sending or relaying traffic. When a node sends a packet, it pays credits to relay nodes for forwarding its packet. If a relay node actively forwards packets, it would earn many credits and send its own packets later by spending credits [7]. Since credits are used as virtual money, each node requires tamper-proof hardware or a centralized authority to ensure every payment among nodes. This condition prevents market-based schemes from becoming a fully distributed algorithm. Instead, [8] proposes a secure protocol to manage credits confidentially without any extra authorization. However, these schemes do not provide all the nodes with equal opportunities to earn their own credits. Nodes at the edge of network are penalized because the demand for relaying traffic is relatively low.

Another approach to stimulate cooperation is a pricing-based scheme where nodes compete for being selected on a routing path. The pricing scheme was initially introduced into networks as a rate-control problem in [9], and has been developed to design network resource allocation problems with dynamic link costs. In this scheme, relay nodes competitively bid their resources to accommodate as much incoming traffic as possible, and then the next-hop is decided depending on the link costs. Since every node only cares to maximize its own profit, this approach is usually modeled with a game-theoretic framework. In [10], the interaction among nodes is considered as a Stackelberg competition to solve revenue-maximization problems. Recently, [11] analyzes the multi-hop pricing game with a game-theoretic perspective where a relay competes for traffic from multiple nodes and allocates received traffic to multiple nodes. However, the selected routing path is not guaranteed to be the shortest path to a destination even though it could be optimal for each node to achieve its own profit. This result can cause a delay when packets arrive at a destination and consume more energy than expected.

To mitigate the delay effects, this work assumes that a routing path is decided with the help of a shortest-path algorithm. Given a path, both a sender and a relay cooperate to forward traffic by using the relative reputation of each node. The main differences from the previous approaches are as follows. Instead of isolating non-cooperative nodes on the path, this paper provides non-cooperative nodes with more chances to contribute to the overall network throughput. To encourage them to be cooperative, this work allows mutual bidding of cooperative willingness of a sender and a relay to decide the forwarding probability of packets. Rather than competing for traffic, a relay decides its bidding amount considering the available energy status and the sender's reputation. This inter-relation procedure not only makes a relay conditionally cooperate, but also allows a cooperative sender to be treated well, and a non-cooperative sender to turn into being cooperative.

This paper proposes a cooperative relay scheme under an energy-limited condition in multi-hop networks. The main focuses are 1) to motivate each node to be cooperative, 2) to optimally decide the amount of cooperation, 3) to analyze an equilibrium for the proposed scheme, and thus 4) to maximize the overall throughput. First, each node is treated according to its relative reputation. Unlike the previous mechanisms, this relative reputation increases only when cooperative behavior is in accordance with the proposed rule so that helping a cooperative node is encouraged while helping a selfish node is discouraged. Second, this work formulates a mutual-bidding problem of the Stackelberg competition. By embedding a sequential-move game, the inter-relation between two nodes is modeled as an optimization problem. Third, an equilibrium of the optimal solution is analyzed compared to a simultaneous-move game of Cournot competition [12]. Simulation results show that each node is encouraged to be a cooperative node and the total network throughput is effectively improved as opposed to a conventional scheme where selfish nodes are isolated, and thus, are not allowed to contribute to relay packets any longer. The key contributions of this work are

- The cooperative rule is a novel approach where only conditional cooperation is encouraged.
- The proposed scheme does not isolate selfish nodes. Instead, the mutual-bidding scheme provides them with more chances to participate in the network.
- The cooperation between nodes is modeled under energy-limited constraint in a game-theoretic framework.
- A two-stage Stackelberg equilibrium is analyzed compared to a one-stage Cournot equilibrium.

II. System Model

This paper considers stationary multi-hop networks where a source sends traffic to a destination through multiple relays with fixed power. It is assumed that a routing path is discovered by Dijkstra's shortest-path algorithm and consists of loop-free links in multi-hop networks.

This work assumes that a sender can precisely estimate its own channel gain to a specific relay [13]. Since a block fading channel is considered, the channel gain on a link is invariant over the block period so that a sender can be reasonably aware of it. The corresponding signal-to-noise ratio (SNR) can be calculated, and accordingly, the network throughput of each link can be obtained. In the network, it is also assumed that each node overhears control packets from neighboring nodes. By overhearing the packets, each node can monitor its neighbors and record their cooperative activities in its look-up table. In the proposed scheme, this look-up table is utilized for itself in order to avoid any security concerns among nodes.

III. Cooperative Relay Scheme

The proposed cooperative scheme is based on the Stackelberg competition between a sender and a relay. In multi-hop networks, a sender needs to ask a relay to forward its packets toward the destination. The relay responds to the sender about whether or not to relay the packet. This sequential procedure can be modeled by the Stackelberg competition and the optimal strategy is solved by backward-induction.

To encourage a relay to forward a packet, the proposed scheme provides an incentive if it transmits the packet successfully. However, it is possible that a malicious node takes advantage of the scheme such that it transmits only its own packets as a selfish sender and does not participate in forwarding any other packets as a relay. Therefore, a new rule of the game is designed in such a way that an incentive is provided only when a relay helps a cooperative sender or denies to help a non-cooperative sender. To determine how cooperative a sender is, this paper re-defines the term, *credit*, not as virtual money, but as a history of how well a node follows the proposed scheme's rule. This credit is in the range of $[-1, +1]$. The most cooperative node has a credit of $+1$ and the most selfish node has a credit of -1. The credit is updated after each game is over as follows:

$$c_{i,n+1} = c_{i,n} + \Delta c_i \tag{1}$$

where $c_{i,n}$ is the credit of node i at time n and Δc_i is the amount of the incentive credit, which is achieved by the chosen action. Note that the updated credit $c_{i,n+1}$ is bounded at ± 1.

Table 1 shows how the credit of a relay changes depending on its action. The credit is given only when it helps to forward a packet from a cooperative node and denies to help a selfish node. This scheme encourages nodes to be cooperative in order to avoid being treated as a selfish sender later.

Table 1. The Credit Table of Relay

sender	action	Δc_r
cooperative	forward	rewarded (+)
cooperative	drop	punished (-)
selfish	forward	punished (-)
selfish	drop	rewarded (+)

The credit of a sender represents the reputation it has achieved from other nodes. The reputation declines from neighbors when a request to forward its packet is refused by a relay. Since a sender cares about only whether its packet is successfully delivered or not, the incentive credit to a sender depends only on the action of the relay, as in Table 2.

Table 2. The Credit Table of Sender

relay	action	Δc_s
-	forward	gain reputation (+)
-	drop	lose reputation (-)

Based on the incentive strategy, this paper addresses the problem of how cooperative a node is each time. The game introduces a new variable w_i to represent the *willingness* to participate in the game. Both a sender and a relay should be able to decide their own willingness, and correspondingly, the forwarding probability at time n is expressed in terms of credits and willingness as

$$p_n = p_{\text{base}} + p_{\text{const}} \sum_{i=r,s} w_i c_{-i,n} \tag{2}$$

where p_{base} and p_{const} are tuning parameters, and the subscript $-i$ represents the opposite player. Each node looks at the credit of the opposite player and decides how much it weighs. If a node meets a cooperative player, then it would weigh more to increase the forwarding probability, and vice versa.

With these parameters, the game between a sender and a relay is established. Each node has two utilities consisting of three components: Shannon's capacity as the measure of the throughput, the cost of consuming transmission power, and the credit accumulation as its reputation. Given the transmission cost β, and the SNRs in the game, both throughput utility and credit utility are expressed as

$$u_{t,i}(w_i, w_{-i}) = p_n \left(\log\left(1 + \text{SNR}_i\right) - \beta\right), \tag{3}$$

$$u_{c,i}(w_i, w_{-i}) = f_i(p_n, c_{-i,n}) w_i \tag{4}$$

where SNR_s is the SNR between a sender and a relay, and SNR_r is the SNR between a relay and the next hop of the relay. The amount of credit is calculated based on Table 2 and 3. When a relay weights its willingness w_r, it gains or loses additional credit depending on a sender's current credit and whether the packet is actually forwarded after the game is over. Therefore, $\Delta c_r = \pm c_s w_r$ and $f_r(x, y) = (2x - 1)y$ where $\pm$ signs follow Table 1, and $[0, 1]$ is mapped to $[-1, 1]$ by $(2x-1)$, allowing the credit utility $u_{c,i}$ to be positive, i.e., giving an incentive, or negative, i.e., giving a penalty. From the perspective of a sender, the additional credit relies only on its willingness w_s, and the result of the actual packet delivery regardless of the current credit of a relay. Thus, $\Delta c_s = \pm w_s$ and $f_s(x, y) = (2x - 1)$ where $\pm$ signs follow Table 2.

Furthermore, the game has one constraint such that a node should be operating under the available battery condition. Each time, a node could be requested or request to join in the game. According to the result of each game, the remaining energy of node i at time n, notated as $\beta_{\text{rem},i,n}$, varies as

$$\beta_{\text{rem},i,n} = \beta_{\text{tot}} - \sum_{k=1}^{n-1} I(p_k)\beta > 0 \quad \text{for } i = r, s \tag{5}$$

where β_{tot} is the total energy resource of each node and $I(\cdot)$ is the function to indicate the result of packet delivery.

$$I(p_n) = \begin{cases} 1 & \text{if packet is successfully delivered under } p_n \\ 0 & \text{otherwise} \end{cases}$$

The objective function of each node is then the sum of the physical utility $u_{t,i}$ and the virtual utility $u_{c,i}$ above under the condition that each node is alive. The *cooperation factor* α controls the weight of the virtual utility. Accordingly, the game between a sender and a relay leads to two sequential optimization problems so as to maximize the objective function. For a relay, the best response w_r^* is a function of given w_s, i.e., $w_r^* = w_r^*(w_s)$. This optimization problem is

$$\begin{aligned} \max_{w_r \in W} \quad & \pi_r(w_r, w_s) = u_{t,r}(w_r, w_s) + \alpha u_{c,r}(w_r, w_s) \\ \text{subject to} \quad & \beta_{\text{rem},r,n} - p_n \beta > 0 \end{aligned} \tag{6}$$

where W is the feasible set bounded by the maximum and minimum limit of the willingness variable. Notice that $W = [w_{min}, w_{max}]$ where $0 \leq w_{min},\ w_{max} \leq 1$. On the other hand, a sender is able to anticipate how a relay would behave given w_s, i.e., $w_r^* = w_r^*(w_s)$ by backward-induction as shown before. The sender's optimization is expressed as

$$\begin{aligned} \max_{w_s \in W} \quad & \pi_s(w_s, w_r^*) = u_{t,s}(w_s, w_r^*) + \alpha u_{c,s}(w_s, w_r^*) \\ \text{subject to} \quad & \beta_{\text{rem},s,n} - p_n \beta > 0. \end{aligned} \tag{7}$$

By solving two sequential optimization problems, both sender and relay can decide their best strategies to maximize their own payoffs.

IV. Equilibrium Analysis

This section shows that the proposed strategy motivated by a sequential-move game through Stackelberg competition achieves a Nash equilibrium, and it is unique for each player. Additionally, strategies by a simultaneous-move game through Cournot competition cannot be achieved in practice.

At the first stage of the Stackelberg game, a sender anticipates that a relay rationally decides its best strategy based on the proposed rule. Given all the available information, a sender estimates the relay's response by solving its optimization problem in Eq. (6). This problem can be rewritten as a quadratic form of w_r by

$$\begin{aligned} \max_{w_r \in W} \quad & \pi_r(w_r, w_s) = a w_r^2 + b w_r + c & \\ \text{subject to} \quad & w_r \leq d & \text{if } c_{s,n} > 0 \\ & w_r \geq d & \text{if } c_{s,n} < 0 \\ & \beta_{\text{rem},r,n} - (p_{\text{base}} + p_{\text{const}} w_s c_{r,n})\beta \geq 0 & \text{if } c_{s,n} = 0 \end{aligned}$$

where the variables, a, b, c, and d, are defined respectively as

$$\begin{aligned} a &= 2\alpha p_{\text{const}} c_{s,n}^2, \\ b &= \left(2\alpha p_{\text{const}} c_{r,n} c_{s,n}\right) w_s + p_{\text{const}} c_{s,n} A_r + \alpha c_{s,n}(2p_{\text{base}} - 1), \\ c &= (p_{\text{base}} + p_{\text{const}} w_s c_{r,n}) A_r, \\ d &= -c_{r,n} w_s / c_{s,n} + \left(\beta_{\text{rem},r,n} - p_{\text{base}}\beta\right) / \left(c_{s,n}\beta p_{\text{const}}\right), \\ A_r &= \left(\log\left(1 + \text{SNR}_r\right) - \beta\right). \end{aligned}$$

Then, the optimal strategy of a relay $w_r^*(w_s)$ is expected to be one of three solutions below as a function of w_s depending on certain conditions (which are omitted because of space constraints).

$$w_r^*(w_s) = \begin{cases} w_{\max} \\ w_{\min} \\ -\frac{c_{r,n}}{c_{s,n}} w_s + \frac{\beta_{rem,r} - p_{\text{base}}\beta}{c_{s,n}\beta p_{\text{const}}} \end{cases}$$

At the next stage, a sender applies the solution of $w_r^*(w_s)$ to its own objective function $\max_{w_s \in W} \pi_s\left(w_s, w_r^*(w_s)\right)$ and decides the best strategy w_s^* by solving a similar quadratic optimization problem. Sequentially, a relay decides its strategy $w_r^*(w_s^*)$ after receiving a sender's response w_s^*.

A. Stackelberg Equilibrium

Proposition 1 *In the proposed two-stage game, the backward-induction solution* $\mathbf{w} = (w_s^*, w_r^*(w_s^*))$ *is a Nash equilibrium.*

Proof: The solution set $\tilde{\mathbf{w}} = (w_s^*, w_r^*(w_s))$ of two nodes is a Nash equilibrium because both strategies of the nodes are the best responses to each other. At the first stage, w_s^* is the best response to $w_r^*(w_s)$ so that it maximizes the objective function $\pi_s(w_s, w_r^*(w_s))$. At the second stage, $w_r^*(w_s)$ is also the best response to w_s so that it maximizes the objective function $\pi_r(w_s, w_r)$. The backward-induction solution $\mathbf{w} = (w_s^*, w_r^*(w_s^*))$ is achieved when the best response w_s^* of a sender to a relay is given. Since a set $\mathbf{w}$ is a subset of the set $\tilde{\mathbf{w}}$, the backward-induction solution achieves a Nash equilibrium. ■

Theorem 1 *The proposed two-stage game guarantees the existence of a solution if*

$$\beta_{rem,i,n} \geq \beta \quad \textit{for } i = r, s$$

and the solution is unique unless the following two conditions occur: $c_{s,n} = 0$ *or* $a = -b, d \notin W$.

Proof: The optimization problem for a relay is a quadratic problem of w_r with an affine constraint of energy. As long as the available transmission energy remains, the solution of a quadratic objective function $\pi_r(w_r, w_s)$ is on a valid finite set W. This condition verifies the existence of the solution w_r^*. Since the sender's optimization problem consists of a linear function w_r^* of w_s for an expected response from a relay, the objective function $\pi_s(w_s, w_r^*)$ is still quadratic. Therefore, provided the valid energy constraint, the finite set W also guarantees the existence of the solution w_s^*.

The backward-induction solution $\mathbf{w} = (w_s^*, w_r^*(w_s^*))$ is unique except under two conditions: The first is that a sender is exactly neutral. According to Table 1, a relay's action is decided depending on the credit of a sender. Thus, a node with a neutral credit can be both cooperative and selfish so that a relay is confused about whether to help or not. The second is that d is outside a region W so that a whole region W is valid in an energy constraint, i.e., $d \notin W$, and simultaneously the quadratic objective function is symmetric in a feasible set W, i.e., $a = -b$. This condition gives a symmetric quadratic form within a feasible set W. Similarly, the same condition is applied when a sender solves its own optimization problem. Except for these cases, the convexity or concavity of a quadratic problem is maintained so that a unique solution is obtained from an asymmetric region of a feasible set. ■

B. Cournot Equilibrium

The proposed scheme is based on a sequential-move game to decide the best strategies for a sender and a relay. From a game-theoretic perspective, two nodes can simultaneously exchange their biddings. This simultaneous-move game is explained by the Cournot competition where each player decides his own strategy without seeing other players' actions. However, this subsection shows that the proposed scheme cannot achieve a solution from the Cournot competition.

Theorem 2 *The simultaneous one-stage game for the proposed model does not guarantee that the best response* (w_s^*, w_r^*) *for both nodes exists or is unique even if it exists.*

Proof: Provided that the proposed scheme is operated in a one-stage game, a sender seeks its solution w_s^* directly from the optimization problem in Eq. (7) as a function of w_r. Using its own quadratic problem, the optimal strategy for a sender $w_s^*(w_r)$ is developed in one of four options as follows:

$$w_s^*(w_r) = \begin{cases} w_{\text{max}} \\ w_{\text{min}} \\ -\frac{c_{s,n}}{c_{r,n}} w_r + \frac{\beta_{rem,s} - p_{\text{base}}\beta}{c_{r,n}\beta p_{\text{const}}} \\ -\frac{c_{s,n}}{2c_{r,n}} w_r + \frac{c_{s,n} A_s}{4\alpha c_{r,n}} - \frac{2p_{\text{base}} - 1}{4p_{\text{const}} c_{r,n}} \end{cases}$$

where $A_s = \log\left(1 + \text{SNR}_s\right) - \beta$. Since two functions of $w_r^*(w_s)$ and $w_s^*(w_r)$ are the best responses to each other, any crossing points become optimal for both. However, the slopes of the linear regions of $w_r^*(w_s)$ and $w_s^*(w_r)$ are the same, or have the same sign depending on their parameters. Under this condition, two linear regions of $w_r^*(w_s)$ and $w_s^*(w_r)$ could be parallel, overlapped, or unmatched.

Thus, the simultaneous one-stage game may not have a solution or may have multiple solutions. When the strategy of each node is not unique, another node cannot decide its own strategy, and thus, should decide at random. This simultaneous setting prevents the proposed model from obtaining the optimal solution. ■

V. Relay Protocol and Successive Games

This section explains the underlying relay protocol where the proposed cooperative scheme operates. The proposed scheme is based on a two-stage game between a sender and a relay, and this game is repeated along a given routing path toward a destination.

A game between a sender and a relay is established with two phases. When a sender is ready to send its messages, it sends a control signal to its next-hop in the first phase. If the designated relay is under the powerless state, it would reject the game and remain selfish because it is more important to save energy for its own transmission later. Otherwise, the relay responds with an ACK signal with the associate game parameters such as the SNR of the next link. In the second phase, a sender searches the relay's credit and cooperative activities in its look-up table, which has been accumulated by overhearing its neighbors. Then, it decides the best response to maximize its own profit and sends the best response to the relay. Using this procedure, the proposed cooperative scheme continues until the packet reaches the destination.

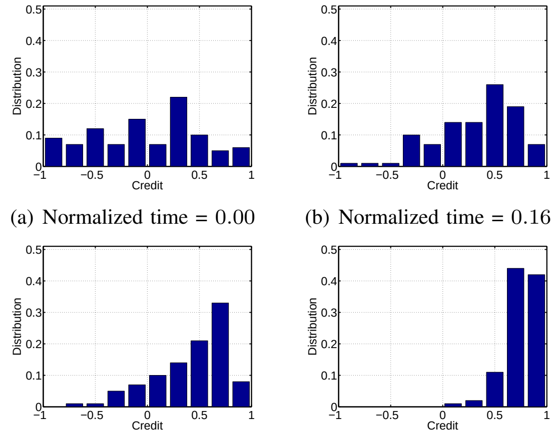
If the destination directly receives a packet from the prior game, no additional procedure is necessary. On the other hand, if a relay's next relay turns out to be the final destination, the relay just forwards the packet to the destination without a subsequent game and accumulates the maximum credit. This is because the packet was originally headed to the destination, so a game does not need to be established.

In this series of successive games, the next hop of a relay plays the role of a sender according to Table 2. For example, when a routing path, $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \cdots$, is decided, node 1 initiates the first game with node 2 and the packet is relayed to node 3 according to the forwarding probability of the game. If node 3 successfully receives the packet from node 2, node 3 would begin a successive game as a sender with node 4. This work assumes that once a node receives a packet, it broadcasts an ACK signal to its neighbors so that the neighboring nodes can monitor whether the relay node intentionally drops the packet at the next supposed transmission. If the node does not begin the successive game, i.e., drops the packet intentionally, it will lose credits because it is monitored by its neighbors. Through this framework, all the nodes on the routing path are encouraged to participate in the proposed games.

VI. Simulation Results

This section presents the simulation results for evaluating the performance of the proposed relay scheme. The proposed scheme is implemented in MATLAB for the purpose of algorithmic validation. A network with 100 nodes is simulated at the network level where the nodes are uniformly distributed over the area of 1000 m $\times$ 1000 m. Although the simulations do not take into account networking issues such as packet losses due to the volatility of wireless links or congestions, the simulations empirically verify the correctness of the algorithm and feasibility of the protocol. A simple unit-disk graph model is used for network connectivity, and the maximum radio range for successful transmission is set to 200 m. The transmission power level of each node is set to 0 dBm, and the environment noise is assumed to be an additive white Gaussian with mean zero and variation -90 dBm. The propagation model assumes to obey a path-loss model with a constant path-loss factor $K = -31.54$ dB, a reference distance $d_0 = 1$ m, and a path-loss exponent $\gamma = 3.71$ from the set of the empirical measurements for an indoor system at 900 MHz [14], and a log-normal model with mean zero and standard deviation 3.65 dB. For each transport path, a pair of a source and a destination are selected each time, and this end-to-end transmission is repeated for 1000 runs. The total run time is normalized to 1.00. Regarding the game parameters, $p_{\text{base}} = w_{max}/2$, $p_{\text{const}} = 0.25$ are used where $w_{min} = 0.1$ and $w_{max} = 0.9$. The route between a source and a destination is searched by Dijkstra's shortest-path algorithm.

Fig. 1 shows how the distribution of the nodes' credit changes over time. Initially, the credits are uniformly distributed in Fig. 1(a) from the most selfish, -1 to the most cooperative, $+1$. As the proposed relay scheme provides incentives to nodes obeying the rule of the game, the distribution is moved toward the right as in Fig. 1(b) and Fig. 1(c). This movement means that many nodes are changed into cooperative nodes whose credits are greater than 0. At the end of the simulation run, most of the nodes are willing to participate in cooperation as in Fig. 1(d).



(a) Normalized time = 0.00
(b) Normalized time = 0.16
(c) Normalized time = 0.25
(d) Normalized time = 1.00

Fig. 1. Illustration showing how the distribution of nodes' credit changes under the proposed scheme as the normalized time goes from 0.00 to 1.00.

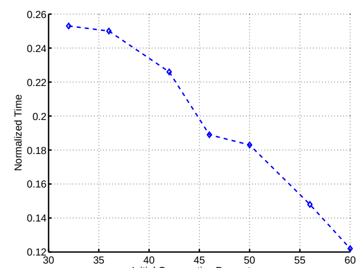
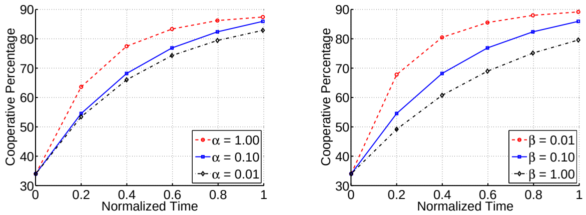


Fig. 2. Required time to reach 70 percent cooperative nodes over all the nodes where $\alpha = 1$, $\beta = 0.1$, and $\beta_{\text{tot}} = 100$.

Fig. 2 shows the required time to reach a certain level of cooperative percentage of all the nodes. It is observed that the time needed for 70 percent cooperative nodes over all the nodes decreases as the initial percentage of cooperative nodes increases. This means that the initial cooperative percentage impacts how fast the nodes in the network become cooperative.

The effect of parameters used in payoff functions is shown in Fig. 3. As the cooperation factor α increases, the curve of cooperative percentage of nodes goes up steeply in Fig. 3(a). This reveals that it takes less time to make nodes cooperative because each node puts more weight on the accumulation of the credit rather than other utilities. Fig. 3(b) shows the effect of transmission cost β. As β increases, the node should carefully decide to join the game as a relay because it costs much to forward a packet from a sender. Thus, the increase of β makes it slower to turn nodes into being cooperative.



(a) $\beta = 0.1$ and $\beta_{\text{tot}} = 100$ (b) $\alpha = 0.1$ and $\beta_{\text{tot}} = 100$

Fig. 3. The effect of each parameter: cooperation factor α and transmission cost β, respectively, on the cooperative percentage.

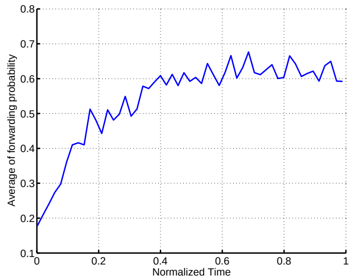


Fig. 4. The forward probability increases as time goes by under the proposed scheme where $\alpha = 1$, $\beta = 0.1$, and $\beta_{\text{tot}} = 100$.

Fig. 4 shows the average forward probability as simulation continues. Under the proposed scheme, it was shown that the number of cooperative nodes increases in Fig. 1. As the entire network gets more cooperative, the forward probability also increases because each node is more willing to help cooperative nodes. This implies that the network is getting cooperative to forward packets with higher forward probability.

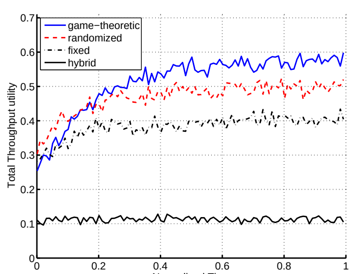


Fig. 5. The total throughput utility under different schemes to decide the willingness w_i with $\alpha = 1$, $\beta = 0.1$, and $\beta_{\text{tot}} = 100$, and a hybrid scheme.

Fig. 5 compares the total throughput utility under different schemes on the decision of the willingness w_i and a conventional scheme to isolate selfish nodes as in [15]. The result demonstrates that the proposed game-theoretic scheme outperforms the other schemes, i.e., the random selection of w_i in $[w_{min}, w_{max}]$ or the fixed use of $w_i = 0.5$, confirming that the game-theoretic w_i selection is the best response through optimization. It is observed that the randomized algorithm has an advantage over the fixed-value method because randomized behavior avoids the worst case of w_i selection. In addition, the total throughput utility of the conventional reputation-based scheme is relatively low since it isolates non-cooperative nodes from the network and inherently prevents them from contributing to relay packets at all. On the other hand, the game-theoretic scheme turns non-cooperative nodes into being cooperative, allowing them to contribute to relay packets.

VII. Conclusion

This paper studies an incentive-based relay scheme to encourage nodes to be cooperative in wireless ad-hoc networks. The proposed scheme takes a game-theoretic perspective so that the payoff of each node can be maximized given the condition that its energy remains available. As a result, it is shown that the distribution of nodes' credit moves toward being cooperative and most of the nodes become willing to help one another under the proposed scheme.

The main benefit of this scheme is in two aspects. First, the proposed scheme is based on a decentralized algorithm. Even if there is no central authority, the network is driven to relay packets from neighbor nodes so that it becomes actively operated. Second, in this work, each node adaptively decides its best response depending on the network environment. In every game, each node can control the amount of its participation to relay packets. Both the forward probability of a relaying packet and the amount of energy consumption can be effectively managed by its rational behavior. For these reasons, the proposed scheme fits well into wireless ad-hoc networks where each node is self-operating.

References

[1] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. on Information Theory*, vol. 51, no. 9, pp. 3037–3063, Sep. 2005.

[2] S. Marti, T. J. Giuli, K. Lai, and M. Baker, "Mitigating routing misbehavior in mobile ad hoc networks," in *6th Annu. ACM/IEEE Int. Conf. Mobile Computing and Networking*, 2000, pp. 255–265.

[3] Q. He, D. Wu, and P. Khosla, "SORI: A secure and objective. reputation-based incentive scheme for ad-hoc networks," in *IEEE WCNC'04*, 2004.

[4] P. Micardi and R. Molva, "CORE: a collaborative reputation mechanism to enforce node cooperation in mobile ad hoc networks," in *IFIP Conf. Security Communications, and Multimedia*, 2002.

[5] A. Urpi, M. Bonucelli, and S. Giordano, "Modeling cooperation in mobile ad hoc networks: A formal description of selfishness," 2003.

[6] V. Srinivasan, P. Nuggehalli, C. F. Chiasserini, and R. R. Rao, "Cooperation in wireless ad hoc networks," in *IEEE Infocom'03*, 2003.

[7] L. Buttyán and J.-P. Hubaux, "Stimulating cooperation in self-organizing mobile ad hoc networks," *ACM/Kluwer Mobile Networks and Applications*, vol. 8, no. 5, pp. 579–592, Oct. 2003.

[8] S. Zhong, J. Chen, and Y. R. Yang, "Sprite: A simple, cheat-proof, credit-based system for mobile ad hoc networks," in *IEEE Infocom'03*.

[9] F. Kelly, A. Maulloo, and D. Tan, "Rate control in communication networks: shadow prices, proportional fairness and stability," *Journal of the Operational Research Society*, vol. 49, 1998.

[10] T. Basar and R. Srikant, "Revenue-maximizing pricing and capacity expansion in a many-users regime," in *IEEE Infocom*, 2002.

[11] Y. Xi and E. M. Yeh, "Pricing, competition, and routing for selfish and strategic nodes in multi-hop relay networks," in *IEEE Infocom*, 2008.

[12] R. Gibbons, *Game Theory for Applied Economists*. Princeton University Press, 1992.

[13] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. New York, NY, USA: Cambridge University Press, 2005.

[14] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge University Press, 2005.

[15] M. T. Refaei, V. Srivastava, L. DaSilva, and M. Eltoweissy, "A reputation-based mechanism for isolating selfish nodes in ad hoc networks," in *MobiQuitous'05*, 2005.