Analysis of A Hybrid Reputation Management System for Mobile Ad hoc Networks

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***Abstract*—In cooperative systems such as wireless ad hoc networks, tasks are conducted based on the cooperation of nodes in the system. However, selfish nodes may refuse to be cooperative. Reputation system and price-based system are two main solutions to this problem. In this paper, we use game theory to investigate the underlying cooperation incentives of both systems. We found that the strategies of using a threshold to determine the trustworthiness of a node in the reputation system and of rewarding cooperative nodes in the price-based system may be manipulated by clever selfish nodes to gain benefits while still being selfish. Illumined by the investigation results, an integrated system is proposed and studied. Theoretical and simulation results show the superiority of the integrated system over individual reputation system and price-based system in terms of the effectiveness of cooperation incentives.**

I. Introduction

Cooperative systems such as wireless mobile ad hoc networks (MANETs) require the cooperation of every node in the path for successful message transmission. However, since the nodes in these applications are usually constrained by limited power and computation resources including CPU, battery and etc., these nodes (human) may not be willing to be cooperative in order to save their limited resources. The presence of only a few non-cooperative nodes can dramatically degrade the performance of an entire system [1].

Recently, a considerable amount of work has been proposed to deal with the non-cooperation problem in cooperative system such as MANETs. They generally can be classified into two main categories: reputation system and price-based system. The basic goal of reputation systems [1–7] is to evaluate each node's trustworthiness based on its behaviors and detect misbehaving nodes according to reputation values. Reputation systems enable each node to maintain a reputation table recording the reputation values of other nodes. Most reputation systems set up a reputation threshold to distinguish the misbehaving nodes and cooperative nodes. Nodes whose reputation values are lower than the threshold are regarded as selfish nodes. During message routings, nodes refuse to forward data for selfish nodes. A node selects cooperative nodes as relay nodes and avoids selfish nodes in message routing. Price-based systems [8–11] treat message forwarding services as transactions that can be priced, and introduce virtual cash such as credits to manage the transactions between nodes. A service receiver pays credits to a service provider that offers forwarding service.

Game theory [12] is a theory of applied mathematics that models and analyzes the interactive decision situations. In this paper, we use game theory to model and study the individual reputation system and price-based system, and analyze their underlying incentives and inherent deficiencies. We found that the incentives of both systems can encourage nodes to be cooperative to a certain extend. The strategies of using a threshold to determine the trustworthiness of a node in the reputation system and the strategies of rewarding cooperative nodes in the price-based system may be manipulated by clever selfish nodes to gain benefits while still being selfish. In addition, we also propose an integrated system combining reputation system and price-based system. The integrated system leverages the advantages of both systems and overcomes their individual disadvantages, making the potential reciprocity the focal point of integration. We build a game theory model for analyzing the integrated system.

The remainder of this paper is organized as follows. Section II provides relative works. Section III presents the analysis based on game theory for individual reputation systems price-based systems and the proposed integrated system. Section IV presents the simulation results. Section V concludes the paper.

II. Related works

Reputation systems and price-based systems are two main approaches proposed to encourage the cooperation between mobile nodes in MANETs. A reputation system gathers observations of node behaviors and calculates node reputation values [1–7] The system detects low-reputed nodes and punishes these nodes by isolating them of the MANET. Most of the reputation systems use a threshold to distinguish selfish nodes from cooperative nodes. However, clever selfish nodes can wisely maintain their reputation value just above the threshold by selectively forward others' messages. These nodes can take advantage of other cooperative nodes without being regarded as selfish nodes. In addition, this method cannot differently award high-reputed nodes or punish low-reputed nodes in different reputation levels.

In the price-based systems, nodes are paid for offering message forwarding service and pay for receiving forwarding service [8–11]. Buttyan and Hubaux [8–10] introduced nuglets as credits for managing forwarding transactions. Two payment models, message purse model and message trade model, were proposed. In the former, a source node pays relay nodes by storing nuglets in the message head. Intermediate nodes acquire nuglets when forwarding the message. In the latter, a relay node buys messages from the previous node and sells them to the next node in the path. The credit-based system in [11] uses credit clearance service and message receipts. When a node forwards a message, it keeps a receipt and uploads it to the credit clearance service for credits. Although the price-based system can stimulate nodes to be cooperative, most price-based systems fail to provide a way to know the service quality of a node. Moreover, they fail to punish a selfish and wealthy node that earns many credits by cooperating but drops others' messages later on. Furthermore, the nodes that do not need forwarding services can always refuse to help others to forward packets.

Another group of approaches aim to encourage the node cooperation without incentive mechanisms. Srinivasan and *et al.* [13] proposed a distributed and scalable acceptance algorithm called Generous TIT-FOR-TAT (GTFT). The algorithm is used by the nodes to decide whether to accept or reject a relay request. In [14], Felegyhazi and *et al.* addressed the problem of whether cooperation can exist without incentive mechanisms. They proposed a model based on game theory and graph theory to investigate equilibrium conditions of packet forwarding strategies: cooperative and non-cooperative. However, only depending on interaction strategies may not maximum the system performance. The strategies enable nodes to receive better benefits, but cannot detect and punish the misbehavior of selfish nodes. In [15], we proposed a ARM system, which combine the advantages of both reputation system and price-based system and give some preliminary results. In this paper, we present more detailed analysis of the effectiveness of the reputation system, price-based system and integrated system and analyze it in the repeated games in addition to the single-interaction game.

III. Analysis of Cooperation Incentive Strategies

We take MANETs as a case to study the cooperation incentives of different cooperation encouraging systems.

Definition 1. A Nash Equilibrium (NE) is an action tuple that corresponds to the mutual best response. Formally, the action tuple $\bar{\mathbf{a}} = (\bar{a_1}, \bar{a_2}, \bar{a_3}, ..., \bar{a_n})$ is a NE if $u_i(\bar{\mathbf{a_{-i}}}; \bar{a_i}) \geq u_i(\bar{\mathbf{a_{-i}}}; a_i)$ for $\forall a_i \in A_i$ and for $\forall i \ \in N$ [16], where A_i denotes the action set (cooperative, non-cooperative) for node i and $\{u_i\}$ denotes a set of utility functions that node i wishes to maximize. Therefore, a NE is an action set where no individual rational node can benefit from unilateral deviation.

Definition 2. An outcome of a game is non-Pareto-optimal if there is another outcome which would give both players higher payoffs, or would give one player the same payoff but the other player a higher payoff. An outcome is Pareto-optimal if there are no such other outcomes [12].

TABLE I: Payoff matrix for defenseless systems

		Node j	
		Cooperative	Non-cooperative
Node i	Cooperative	(p-c, p-c)	(-c, p)
	Non-cooperative	(p, -c)	$(0,0)^*$

A. Game Theory Model for Defenseless Systems

In an interaction, a node forwards message to a relay node. The relay node consumes energy in receiving, processing and transmitting the message. The cost of a message forwarding depends on a number of factors such as channel condition, file size, and modulation scheme. We assume the cost for a node to forward a message is c. We also assume the benefit gained by a node for forwarding a message is p, and $p > c$. Then, the payoff of each node when both nodes are cooperative is $(p - c)$. If one node is non-cooperative in transmitting message and another node is cooperative in transmitting the message, then the non-cooperative node earns a profit of p, while the cooperative one gets a profit of $-c$. This is because the message of the non-cooperative node has been sent by the cooperative node, and the non-cooperative node does not cost any resource. If both nodes are non-cooperative in forwarding messages, the payoff of this action set is $(0, 0)$ because both nodes gain no benefits and cost no resources.

Table I shows the payoff matrix of the combination of different actions taken by node i and node j. From the figure, we can see that since $p > p - c$ and $-c < 0$, no matter which strategy node j chooses, I is the best strategy for node i. Since p>c, no matter what strategy node i takes, I is also the best strategy for node j. Therefore, action set (I_i, I_j) is the NE in this interaction. However, (I_i, I_j) is not the optimal outcome, since (C_i, C_j) leads to payoff $(p - c, p - c)$ which is much higher than $(0, 0)$.

Repeated game. Since in the real system, the interactions between nodes are repeated, we also analysis the cooperation incentives in the repeated game. TIT-For-TAT has been recognized as the most effective interaction strategy so far [12]. In *TIT-For-TAT*, node i is initially being cooperative to another node. If the other node is also cooperative, node i will continuously use C strategy. However, if the other node is non-cooperative, node i will be non-cooperative to this node at the next time. Since (C_i, C_j) is the best outcome of the interaction, node i will later be cooperative to this node again to check if the node wants to be cooperative.

However, iterative defenseless system (IDS) with TIT-For-TAT cannot be used to encourage the cooperation of nodes, if the nodes in the system are not stable. The fundamental reason is that, (C_i, C_j) action set is Pareto-optimal but NE in IDS system. That is, the strategy I is always dominate the strategy C. Therefore, for a finite interaction repeated game, nodes deviating in the last round from (C_i, C_j) can make the node a better payoff. If every node behaves like this, the trust relationship between interacting nodes will break down. As a result, the only resolution to this problem is to make the (C_i, C_j) action set to be NE and Pareto-optimal. In this situation, since the (C_i, C_j) is both NE and Pareto-optimal, each node can gain the same payoff or even higher

TABLE II: Payoff matrix for reputation systems

		Node j	
		Cooperative	Non-cooperative
Node i	Cooperative	(p-c, p-c)	$P(C_i, I_j)$
	Non-cooperative	$P(I_i, C_j)$	(0, 0)

$$P(C_i, I_j) = \begin{cases} (-c, p) & \text{if } R_{I(j)} > R_t \\ (0,0) & \text{if } R_{I(j)} \leq R_t \end{cases} \quad (1)$$

$$P(I_i, C_j) = \begin{cases} (p, -c) & \text{if } R_{I(i)} > R_t \\ (0,0) & \text{if } R_{I(i)} \leq R_t \end{cases} \quad (2)$$

payoff when its opponent deviates its current action no matter in which interactions. Since each node has no incentives to deviate the current cooperation strategy and is not afraid the other's deviation during the interaction as the current strategy is NE and Pareto-optimal. The second problem of IDS with TIT-For-TAT is that IDS can only provide the best action strategy to get the best benefit based on other nodes' actions. IDS cannot monitor, detect and punish the misbehavior in an efficient way.

Proposition 3.1: How to stimulate the cooperation between mobile nodes in a cooperative system which is a finite repeated game, is essentially how to make the action set (C_i, C_j) to be NE and also Pareto-optimal in the payoff matrix.

Proof: One feature of repeated game with TIT-For-TAT strategy is it can change the Pareto-optimal strategy in payoff matrix also to be NE in they interact with each other for infinite times. Therefore, two methods can be enforce the action set (C_i, C_j) to be NE and also Pareto-optimal. One method is (C_i, C_j) is Pareto-optimal, but not NE in the payoff matrix and the other is (C_i, C_j) is Pareto-optimal, but NE in the payoff matrix. However, because the nodes in the system may randomly leave or join the network, the MANET is a finite game, which cannot be solved by TIT-For-TAT strategy. Therefore, we can only stimulate the cooperation between mobile nodes in a MANET by make the action set (C_i, C_j) to be NE and also Pareto-optimal. ■

B. Game Theory Model for Reputation Systems

Most reputation systems use reputation threshold to distinguish selfish nodes from cooperative nodes. If some nodes are cooperative in message forwarding, the reputation values of these nodes are increased by the monitoring nodes. If some nodes are detected to be uncooperative, their reputation values will be reduced. When the reputation value of a node is below a threshold, its routing requests will be refused by others. Table II and Equation (1) and (2) illustrate the payoff matrix for reputation systems. We can see that when the reputation value of the node is above the reputation threshold, non-cooperative action set (I_i, I_j) with payoff $(0, 0)$ is NE, but (C_i, C_j) is Pareto-optimal. Only when the reputation value of the node is below the reputation threshold, the (C_i, C_j) action set weakly dominates the (I_i, I_j), which means (C_i, C_j) becomes NE and Pareto-optimal.

Proposition 3.2: The strongest incentive strategy provided by reputation systems will result in a situation where node reputation values are just above the reputation threshold.

Proof: As the payoff matrix in Table II shows, when the reputation value of a node is above the reputation threshold R_t, the node will be non-cooperative. Then, its reputation value continues to decrease as $\lim_{x \to R_t^+} P(x) = P(R_t)$. On the other hand, when a node's reputation value is below the threshold R_t, the node will cooperate to increase its reputation. The value continues to increase as $\lim_{x \to R_t^-} P(x) = P(R_t)$. Therefore, the reputation values of nodes will converge at R_t, which means that the nodes are likely to keep their reputation value to the threshold. ■

Proposition 3.2 implies that reputation systems cannot provide incentives to encourage nodes to be more cooperative. It can only encourage nodes not to be regarded as misbehaving nodes. If a node cleverly manipulates this policy by accepting partial transmission requests to keep its reputation just above the threshold, the performance of the system is degraded due to the message droppings.

Based on the analysis, we can see that the simple threshold-based strategy potentially reduce the nodes' enthusiasm to be highly cooperative. Instead, they are all willing to keep their reputation just above the threshold. Therefore, a reputation system needs to have a complementary method to encourage all the nodes to be highly cooperative to each other and differentially reward nodes in different altruistic levels.

Repeated game. In the reputation single-interaction game, for a game of two nodes i and j, Pareto-optimal action set alternates between (C_i, C_j) and (I_i, I_j) as the reputation value of the nodes fluctuates near the reputation threshold. Although the (C_i, C_j) is the pareto-optimal at all the time, because (C_i, C_j) cannot always be the NE, the nodes still will not always choose C_i, C_j as their action strategy. Therefore, the (C_i, C_j) strategy in reputation system in the repeated game is not NE and Pareto-optimal.

C. Game Theory Model for Price-based Systems

A price-based system uses credits to encourage node cooperation in the system. If a node does not have enough credits for message forwarding, all of its own transmission requests will be rejected. In addition to the original transmission cost c, and transmission benefit p, we introduce new payoffs m_f and m_p for service transactions. m_f denotes the packet forwarding reward for their cooperative behavior in one interaction, and m_p denotes the packet forwarding price for the packets forwarded by them. Between two nodes with transmission strategies (C_i, I_j), although a non-cooperative node can save the transmission cost c, it should pay m_p for the transmission. Meanwhile, although the cooperative node suffers from message losing payoff p, it can earn a payoff m_f from cooperative behavior to offset the cost. Table III shows a payoff matrix for a pair of interaction nodes, where $\triangle m = m_p - m_f$. For the (C_i, C_j) strategy, since both nodes cooperative for the packet routing, they both earn the payoff p and spend c for the packet transmission. Meanwhile, since each node should pay m_p for the packet forwarding by other and earn m_f for this own cooperative behavior. Therefore, the payoff for (C_i, C_j) is (p-c-$m_p - m_f$, p-c-$m_p - m_f$). Similarly, the payoff for (C_i, I_j) and (I_i, C_j) can be got as Equation (3) and (4) shows.

TABLE III: Payoff matrix for price-based systems

		Node j	
		Cooperative	Non-cooperative
Node i	Cooperative	(p-c-$\triangle m$, p-c-$\triangle m$)	$P(C_i, I_j)$
	Non-cooperative	$P(I_i, C_j)$	$(0, 0)$

$$P(C_i, I_j) = \begin{cases} (-c + m_f, p - m_p) & \text{if } V_j > 0 \\ (0, 0) & \text{if } V_j < 0 \end{cases} \quad (3)$$

$$P(I_i, C_j) = \begin{cases} (p - m_p, -c + m_f) & \text{if } V_j > 0 \\ (0, 0) & \text{if } V_j < 0 \end{cases} \quad (4)$$

Proposition 3.3: In price-based system, the (C_i, C_j) is Pareto-optimal if $p > m_p$ & $m_f > c$.

Proof: [15] shows that if $p > m_p$ & $m_f > c$, then the NE will switch from the (I_i, I_j) to the (C_i, C_j). Meanwhile, (C_i, C_j) is the best outcome in the system. Therefore, (C_i, C_j) is Pareto-optimal. ■

Proposition 3.4: If a wealthy selfish node manages to manipulate its credit amount above zero, the lower bound of the message dropping rate P_d is $\frac{k}{q} \geq \frac{qm_f + V - sm_p}{qm_f}$, where q is the number of messages need the node helps to forward in the first q interactions, s is the number of messages sent by a selfish node and V is the current credit amount [15].

the Equation indicates three situations may lead to a high message dropping rate in a price-based system. First, if a selfish node has considerable amount of credits V, the node can refuse to cooperate with other nodes for a long time. Second, if a node has no need to generate message which means $s = 0$, it can also refuse to forward other's message. Third, when $m_p \ll m_f$, that is, when the packets forwarded price is smaller than packet forwarding award, the system still suffers with high node dropping rate.

The analysis shows that a price-based system can provide effective cooperation incentives to the nodes. However, it fails to detect the misbehavior of some special selfish node.

Repeated game: In the price-based system, according to Proposition 3.3, if $p > m_p$ & $m_f > c$, the (C_i, C_j) strategy is the NE and Pareto-optimal. Therefore, in the repeated cooperation game with finite number of interactions, all the nodes will choose (C_i, C_j) stably and continuously. Therefore, the (C_i, C_j) strategy in price-based system in the repeated game is still NE and Pareto-optimal.

D. Introduction of the Integrated System

An efficient system to encourage the cooperation of the nodes in the system should have two features. (1) Provide strong incentives to encourage the nodes to cooperate for the message forwarding. (2) The system can quickly and effectively detect the non-cooperative node and punish them accordingly. The reputation system is effectively detecting misbehavior by keeping a reputation threshold to distinguish the misbehavior and cooperative behavior. However, it cannot provide incentives for the cooperation of the nodes. Price-based system can provide strong incentive for the messages forwarding, but fails to provide efficient mechanism for misbehaving node detection. Since each system along cannot provide effective way to reduce the misbehaving nodes, we propose an integrated system (IS) combining the reputation system and the price-based system. By integrating the misbehavior detection mechanism of reputation systems and cooperation incentive mechanism of price-based systems, the IS can overcome the individual drawbacks of each system. In the IS, the forwarding service price a node needs to pay is based on its reputation value. A node with higher reputation value needs to pay less prices, while a node with low reputation value should pay much more for the message forwarding service. This avoids discouraging cooperation of high-reputed nodes. Meanwhile, the reputation value of each node is still used to distinguish selfish nodes and cooperative nodes based on a reputation threshold to encourage the wealthy nodes or the nodes have less desire to receive message forwarding service to take part in the messages forwarding. A reputation threshold is also set in the system. If a node's reputation value is below the threshold, no matter how wealthy of the node, its transmission requests will be rejected by other nodes. Meanwhile, its wealthy will be reduced sharply.

TABLE IV: Payoff matrix for the integrated system

		Node j	
		Cooperative	Non-cooperative
Node i	Cooperative	$P(C_i, C_j)$	$P(C_i, I_j)$
	Non-cooperative	$P(I_i, C_j)$	(0, 0)

$$P(C_i, C_j) = (p - c + (m_f - \frac{m_p}{R_i}), p - c + (m_f - \frac{m_p}{R_j})). \quad (5)$$

$$P(C_i, I_j) = \begin{cases} (-c + m_f, p - \frac{m_p}{R_j}) & \text{if } V_j > 0 \text{ \& } R_{I(j)} > R_t \\ (0, 0) & \text{if } V_j \leq 0 \parallel R_{I(i)} \leq R_t. \end{cases} \quad (6)$$

$$P(I_i, C_j) = \begin{cases} (p - \frac{m_p}{R_i}, -c + m_f) & \text{if } V_i > 0 \text{ \& } R_{I(i)} > R_t \\ (0, 0) & \text{if } V_i \leq 0 \parallel\parallel R_{I(i)} \leq R_t. \end{cases} \quad (7)$$

Therefore, the IS can effectively prevent some selfish nodes from keeping their reputation value just above some threshold value. The IS can also encourage wealthy nodes to continue to engage in the message forwarding service to gain a high reputation. The following several sections are used to show the significant performance of the IS according to the game theory model.

Proposition 3.5: (C_i, C_j) in IS is NE and Pareto-optimal if transmission cost c, and packets forwarding reward m_f satisfies $m_f > c$ & $p > c$ [15].

Equation (5) (6) (7) shows that (C_i, C_j) strategy is always the NE and Pareto-optimal if they satisfied $m_f > c$ & $p > c$. Meanwhile, a high reputation value can lead to a high payoff for the cooperation behavior. Therefore, IS can provide higher incentive than price-based system as the reputation of the nodes increase. Since IS is bounded by both reputation threshold and credit amount, it is intuitively that even a node has a considerable amount of credits, if it refuses to cooperate with other nodes, although the credits will not decrease, its reputation value will decrease. If the reputation value is lower than a threshold, the selfish node will be put in to the blacklist. Therefore, the selfish behavior of the nodes with large number of credits and small messages generating requests can be prevented. Meanwhile, a low reputation value leads to a high price for the message forwarding, therefore, the credits of the misbehaving node will be quickly used up. As a result, it is impossible for a node to manipulate a reputation value just above the threshold value.

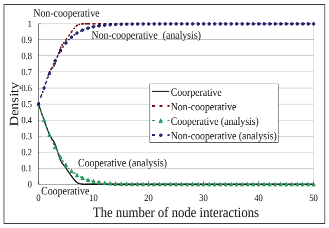

Fig. 1: Defenseless system

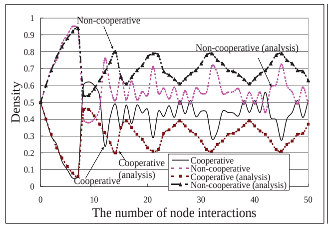

Fig. 2: Reputation system

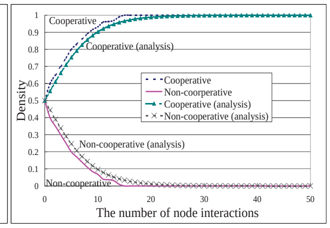

Fig. 3: Price-based system

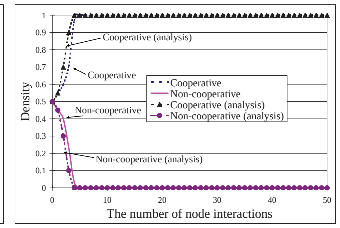

Fig. 4: Integrated system

Repeated game. In the one-interaction game of the IS, (C_i, C_j) action set is NE and Pareto-optimal. Thus, for a repeated cooperation game, each interacting node has no incentive to deviate (C_i, C_j) action set. Even there are some special node deviate the (C_i, C_j), the remaining nodes' payoff will not reduce. Therefore, different from the IDS, nodes in the IS can safely choose cooperation strategy at the all time. Therefore, the IS based MANET is a stable system to provide incentives for the nodes' cooperation. We define the relative success rate of a strategy as the rate of the total payoff of the strategy received to the total payoff of all the strategies.

Proposition 3.6: According to the property of linearity of expectation [17], the percent of the nodes adopting cooperation strategy scales with the relative success rate of the cooperation strategy.

Proof: Suppose initially at round 0, $f_C[0]$ percents of the nodes are cooperative nodes and $f_I[0] = (1 - f_I[0])$ percents are non-cooperative nodes. where $f_C[t]$ and $f_I[t]$ represent the respective percents of action strategy taken by mobile nodes in the each interaction round t. Based on the payoff matrix, the probability of action set happens is (C_i, C_j):(C_i, I_j):(I_i, C_j):(C_i, C_j)=$1:1:1:1$. Suppose the payoff of the (C_i, C_j) action set is represented as $P(C, C)$, the payoff of the cooperation action in (C_i, I_j) is represented as $P(C)$ and non-cooperation action is represented as P(I). Therefore, the rate of the nodes being cooperative to the payoff of the nodes being non-cooperative are

$$f_C[t] = \frac{f_C[0]}{f_C[0] + f_I[0](\frac{[I]}{P(C,C)+P(C)})^{(t-1)}} \quad (8)$$

■

More interestingly, if a current round non-cooperative node changes to be cooperative in the next round, the decrease price of service is $m_p(\frac{1}{R(t)\cdot R(t+1)})$, where R(t) denote the reputation of a node at time t. That is, the smaller R leads to large benefit increase in the next interaction. Therefore, the low reputed nodes are highly encouraged to the cooperated.

IV. Performance Evaluation

In this section, we evaluate the effectiveness of the incentives in the defenseless system, reputation system, price-based system, and the IS in a repeated game, in which the nodes can change their interaction strategies adaptively. We use Monte Carlo simulation [18] to randomly pair up two nodes for interaction. At every game round, each pair of nodes interact with each other once. In the simulation, 100 nodes are independently and identically distributed in the system. There are a mix of 50 cooperative nodes and 50 uncooperative nodes at the start. It was assumed that the node population size stays constant. The number of players using a strategy in the next round is the product of the relative success rate of this strategy in the previous game round and the node population.

In the system, we assume that packet forwarding award is 2 units, packet forwarded price is 1 unit, the transmission benefit is 4 units, and the transmission cost is 2 units. The initial reputation value for each node is 1.0 and the reputation threshold is 0.3. The maximum reputation value is 1. Every time when a node helps to forward a message, its reputation value is increased by 0.1. Otherwise, its reputation value is reduced by 0.1. The assumptions do not affect the relative performance between different systems. We define the density of a strategy as the percent of the nodes employing the strategy among all the nodes. In each figure, the analytical results calculated by Formula (8) are included based on the simulation parameters with individual payoff matrix.

Figure 1 shows the change of the density of nodes in defenseless MANET. The figure shows that after several interactions, the non-cooperative nodes dominate the population of the system. It is because in the defenseless system, the non-cooperative strategy is the NE, but not Pareto-optimal. Since the number of nodes using a strategy depends on the relative success rate of the strategy, the number of players using cooperative strategy decreases sharply because nodes using non-cooperative strategy receive much more payoff. Therefore, the defenseless MANET without any cooperation incentive or misbehavior detection mechanism will finally collapse. Also, from the figure we can see that the simulation results are consistent with the analytical results.

Figure 2 shows the change of the density of nodes in a MANET with reputation system. The figure indicates that in the first $8-9$ interactions, the non-cooperative strategy continues to be the dominant strategy. It is because during these game rounds, the (I_i, I_j) is continually to be NE. The non-cooperative behavior can earn much higher payoff than the cooperative behavior, which results in a dramatic decrease of the population of the cooperative nodes. However, when the reputation values of some nodes fell below the reputation threshold, the payoffs of (I_i, I_j) and (C_i, I_j) and (I_i, C_j) turn to be (0, 0). Therefore, the cooperative strategy is the NE and Pareto-optimal. At this time, since the cooperative action can get much higher payoff than the non-cooperative action, the population of cooperative nodes increases. However, after the reputation values of the nodes increase above the threshold, they will choose the (I_i, I_j) strategy again. Then, the percent of the non-cooperative nodes increase. The figure also shows that the percentages of cooperative nodes and non-cooperative nodes finally approach a constant value, which is the reputation threshold value.

Figure 3 shows the change of the density of nodes in a MANET with price-based system. In the figures, we also include the analytical results calculated by Formula (8) based on the simulation parameters using the payoff matrix for price-based system. The figure shows that cooperative nodes eventually dominate the population of the nodes in the system. It is because in the price-based system, paying forwarding service received and charging forwarding service offered can make (C_i, C_j) action set to be the NE. Unlike the defenseless system where (I_i, I_j) action set is the NE, nodes in the price-based system can earn higher payoff from being cooperative than being uncooperative. Therefore, the number of cooperative nodes increases sharply while that of non-cooperative nodes decreases quickly.

Figure 4 shows the change of the density of nodes in a MANET with the IS. The IS can distinguish the service quality of nodes based on their reputation values which reflect their cooperation degree. In the IS, a lower-reputed node receives lower payoff for providing service, while a higher-reputed node receives higher payoff. Therefore, because the cooperation strategy becomes NE and Pareto-optimal, a cooperative node gets much higher payoff than a non-cooperative node. Therefore, the number of the cooperative nodes is more than the number of non-cooperative nodes. Meanwhile, as the number of game rounds increase, the reputation of the nodes increases. Consequently, the payoff for the action set (C_i, C_j) also increases. This is why the number of non-cooperative nodes in the system drops much faster than the price-based system. Therefore, the IS can provide higher incentives to encourage the cooperation of the nodes in the system than other systems.

V. Conclusions

Cooperative systems such as MANETs require all the nodes in the system to cooperatively conduct a task. How to encourage the cooperation of the nodes is a crucial issue for the proper functions of the systems. Reputation system and price-based system are two main approaches to deal with the cooperation problem in MANETs. Since encourage the cooperation of all nodes in the system to participate in message forwarding is more important than how to just detect the selfish nodes, in this paper, we analyze the underlying cooperation incentives of the two systems in comparison with defenseless system through game theory. To overcome the observed drawbacks in each system, an IS which leverages the advantages of price-based system and reputation system is further proposed. Analytical and simulation results show the higher performance of the integrated system compared to the individual reputation system and price-based system in terms of the effectiveness of the cooperation incentives.

Acknowledgment

This research was supported in part by U.S. NSF grants CNS-0834592 and CNS-0832109.

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