Analysis the Cooperation Strategies in Mobile Ad hoc Networks

Ze Li, Haiying Shen
Department of Computer Science and Computer Engineering
University of Arkansas, Fayetteville, AR 72701
{zxl008, hshen}@uark.edu

Abstract

In mobile ad hoc network, all the packets are forwarded in a multi-hop fashion relying on the contribution of each participants. In order to encourage the cooperation between the nodes in the system, many incentive mechanisms have been proposed. Although these incentive schemes can improve the cooperation to some certain extend, they are still suffering from some drawbacks. In this paper, the efficiency of these incentive mechanisms has been analyzed based on game theory modules. Their performances have also been compared with a proposed hybrid cooperation enforcement mechanism ARM. The simulation and theoretical results show the superiority of the ARM over traditional reputation based scheme and price-based scheme.

1. Introduction

A mobile ad hoc network (MANET) is a self-organized network formed by a collection of mobile nodes without fixed infrastructure management. The packets in the MANET are forwarded in a multi-hop fashion, requiring the contribution of every participant nodes. Recent research shows that the short distance transmission feature of MANET can improve the traditional cellular network in terms of throughput, delay and power efficiency [3]. However, since the mobile nodes in this network are constrained with limited resources, such as CPU, battery, channel bandwidth and etc, some nodes in the network might not be willing to cooperate for the packet transmission, in order to save their resources. Since the MANET is predictable to be deployed for civilian application [13, 11, 8, 17, 23] where no single authority exists for the packets transmission management, the cooperative behaviors between these nodes can not be guaranteed. There might be some nodes intending not to forward packets to save resources for their own use but still seek to use other's resources. The presence of only a few such selfish nodes can dramatically degrade the performance of an entire system [4]. Two types of uncooperative nodes might exist in the system: malicious nodes and selfish nodes. However, in this paper mainly focuses on the selfish nodes since these nodes are the dominant type of nodes in a civilian ad hoc network [24].

Two kinds of systems: reputation-based schemes and pricing-based schemes have been proposed to deal with the incooperative behaviors. Reputation-based schemes [4, 15, 5, 10, 2] set up a reputation threshold to distinguish the selfish nodes from cooperative nodes. Nodes whose reputation value are higher than a threshold are regarded as cooperative nodes, while nodes whose reputation values are lower than the threshold are selfish nodes. Nodes provide services to high-reputed nodes, and refuse to provide services to low-reputed nodes. Therefore, as long as a node has a reputation value that just a little higher than the threshold, it can always be served. This is not fair to high-reputed nodes with different level since they receive the service with the same quality. Reputation-based schemes need to have a complement method to help them wisely punish selfish nodes, and reward altruistic nodes.

Pricing-based model [12, 6, 7, 24] treats packet forwarding as a service that can be priced, and introduce some form of virtual currency to regulate packet forwarding relationships among different nodes. However, only based on the prices is very hard for nodes to know the service quality of each other node. Meanwhile, the nodes with large amounts of virtual credit can still be selfish node in the system.

Other than using incentive mechanisms to encourage the cooperation in MANET, many researchers consider cooperation of entities as the Iterated Prisoner’s Dilemma (IPD) game [21, 16, 19, 9, 22]. Since the mobile nodes in the MANET can be treated as distributed and independent rational entities, IPD can provide a collection of forwarding strategies to achieve the best benefit of the system.

As far as we know, these three mechanisms are developed individually, no further researches to investi-
gate how these mechanisms mutual affect each other. Since we assume the nodes in the MANET are all self-interested, their behaviors is likely to be balanced with a Nash Equilibrium in the system. Thus, the game theory can be a strong foundation to build an effective and stable incentive scheme to encourage the cooperation in the MANET. In this paper, based on game theory models, drawbacks of traditional reputation system and price-based system are analyzed. Their incentive efficiency are also compared with our previous proposed cooperation enforcement mechanism: The hybrid Reputation Management mechanism (ARM) [18]. ARM is a hierarchical reputation system integrated with a global reputation management reputation system and a pricing-based model for effective selfish node punishment. This paper has three contributions. First, the mutual relationship between price-based system, reputation system and game theory are analyzed theoretically. Second, the mechanism of a hybrid reputation management system are testified and analyzed to demonstrate its superior incentive efficiency. Third, several game theory models are proposed to analysis the performance of traditional two systems.

The remainder of this paper is organized as follows. Section 2 provides related works for encouraging nodes cooperation in MANET. In section 3, we demonstrate how does ARM promote the incentive for the mobile nodes cooperation encouragement. Section 4 presents the analysis and simulation results of the performance of ARM in iterated Prisoner’s Dilemma (IPD) game. Section 5 concludes the paper.

2. Relative works

Three classes of approaches are proposed to encourage the cooperation between mobile nodes in MANET. One of them is based on a reputation system which gathers reputation value for each node’s trustworthiness based on the evaluation from others [14, 15, 5, 10]. Marti [14] proposed two techniques, watchdog and pathrater. The watchdog in a node promiscuously listens to the transmission of the next node in the path in order to detect misbehavior. The pathrater in a node keeps the rating of other nodes to avoid any kind of interaction with uncooperative nodes in the transmission. Core [15] uses the watchdog technique and weighs heavily towards past reputation to avoid mistaking cooperative nodes with low battery condition as misbehaving nodes. CONFIDANT [5] detects misbehavior nodes and sends alarm messages to other nodes to isolate misbehaving nodes. Wu and Khosla [10] use the first-hand reputation and second hand reputation to calculate the total reputation of a node. The first-hand reputation of each node is periodically updated and broadcasted to its neighbor when the value is dramatically changes. Anantvalee and Wu [1] introduce a new kind of node which is a suspicious node. The suspicious nodes will be further investigated and if they tend to behave selfishly by a two thresholds to reputation system. However, all these methods only use threshold to distinguish the selfish node. A node can wisely maintain their reputation value above the threshold by selectively forwarding packets.

Another approaches is based on a price-system by using virtual currency, credit or micro-payment [12, 6, 7, 24]. Buttyan and Hubaux [6] use a virtual currency called nuglets to pay for the packet forwarding. Two payment models: packet purse model and packet trade model are proposed by them. In the former, a source node pays relay nodes by storing virtual cashes in the packet-head. Intermediate nodes acquire some nuglets from the packet when they forward it. In the latter, a relay node buys packets from the previous node and sells them to the next node in the path for more virtual cashes. The destination node will eventually pay for these transmission. The credit-based system in [24] uses credit clearance service and message receipts to deal with the selfish nodes in the system. When a node receives a message, the node keeps a receipt of the message and uploads it to the credit clearance service for credits. Although the price system provide a new incentive to the packet forwarding, that is the system increase the payoff of cooperation in the view of game theory, however it can not effectively alleviate selfish behavior when some nodes already have gained a consider amount of virtual credits and they do not want to the cooperate any more.

The third approaches tries to encourage the cooperation between the nodes without incentive mechanisms. They try to model these rational and self-interest nodes with some complex nodes cooperation strategy in a repeated game theory model. Srinivasan in [19] uses the generous TIT-For-TAT mechanism as a node’s strategy in a repeated game for forwarding packets. They also derives a social optimal Nash Equilibrium for that. In [9], Felegyhazi and et al propose a model based on game theory and graph theory to investigate equilibrium conditions of packet forwarding strategies.

3. Analysis of the Incentive Strategies

3.1 Overview of ARM

The basic idea of incentive scheme of ARM is to intelligently integrate reputation system with pricing-based model to avoid selfish nodes. Rather than just using thresholds to detect selfish behaviors, which treats equally to the reputed nodes with different reputation values, ARM use price-module in which the service price of each node is charged based on its reputation.
value in order to avoid discouragement of cooperation of high reputed node. Meanwhile, the reputation value of each node is still used to distinguish the selfish node and cooperative node based on a reputation threshold to encourage the "wealthy" node to take part in the cooperation. More specifically, in ARM, in order to simulate all the nodes to cooperate in packet forwarding, based on the reputation value, every node need pay price for the packet forwarding. A node with higher reputation value need pay less price for the packet forwarding, while the nodes with low reputation should pay more. Therefore, ARM can effectively prevent some selfish nodes from manipulating their reputation value just above some threshold value. ARM can also encourage the nodes with a large sum of virtual cash to continue to engage in the packet forwarding to gain a high reputation. The next several sections are used to show the significant performance of ARM according to the game theory model.

3.2 Game Theory Model

The game theory model for the MANET is defined as follow: Given a normal form of game $G$, $G = \langle N,A,\{u_i\} \rangle$ where $N = \{1,2,\ldots,n\}$ is a set of mobile nodes in a routing path, $A_i$ is the action set for each node $i$, and $A$ is the Cartesian product of the sets of actions to each node. In the MANET, every node has two action, i.e. cooperate or incorporate. $\{u_i\}$ is the set of utility functions that each node $i$ wishes to maximize. For every node $i$, the action chosen by node $i$ is denoted as $a_i$, and the actions chosen by other nodes are denoted as action set $a_{-i}$, that is $a_{-i} = \{a_1, a_2, a_3, \ldots, a_{i-1}, \text{null}, a_{i+1}, \ldots, a_n\}$. Every node does not know what actions the others nodes will adopt. We denote $(a_{-i}; a_i) = \{a_1, a_2, a_3, \ldots, a_{i-1}, a_i, a_{i+1}, \ldots, a_n\}$ as the action set that all the nodes on a path are adopted at one interaction. That is, the actions they adopt for a certain packet's transmission. If there is one node chooses incorporation, the packet will be dropped. Therefore, for every rational node in the system, it intends to choose an action that maximizes its utility function for a given action tuple of the other nodes, that is a best action $a_i \in A_i$ is a best response for node $i$ to $a_{-i}$ iff for all other $a_i \in A_i$,

$$u_i(a_{-i}; a_i) \geq u_i(a_{-i}; a_i)$$

Definition: A Nash equilibrium (NE) is an action tuple that corresponds to the mutual best response. Formally the action tuple $\bar{a} = (a_1, a_2, a_3, \ldots, a_n)$ is a NE if $u_i(a_{-i}; a_i) \geq u_i(a_{-i}; a_i)$ for all $a_i \in A_i$, and for all $i \in N$ [20].

<table>
<thead>
<tr>
<th>Table 1. Prisoner's Dilemma payoff matrix</th>
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<tr>
<td>Node</td>
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<tr>
<td>------</td>
</tr>
<tr>
<td>Cooperate</td>
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<td>Incooperate</td>
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Therefore, a NE is an action tuple where no individual rational mobile can benefit from unilateral deviation. Since the interactions are happened on adjacency nodes in MANET, a two nodes interaction game is modelled to analysis nodes' interactions.

3.3 MANET Without Stimulating Scheme

We assume that in the MANET, every mobile node generates some packets to a neighbor node who serves as a relay node. When two nodes are engaged in a interaction, they can choose a action in the action set (cooperate (C), incorporate (I)). A C action means it helps to node to forward the packet, while a I action indicate it drops the packet. Accounting for all the facts during the transmission, such as interference, energetic cost and so on, we assume the cost for a node to forward a packet is $-c$ where $c > 0$, the benefit of a node's packet is forwarded by others is $p$ where $p > c$. Then the payoff of two cooperative nodes is $(p - c)$. If one node incorporate to transmit packet and another node incorporate to transmit the packet, then the defect one will earn a profit as $p$, while the cooperative one will get a profit as $-c$. If both nodes disagree to forward packets, the benefit is 0; Table 1 shows a interaction payoff matrix of node $i$ and node $j$.

From table 1 we can see that since $p > p - c$ and $-c < 0$, no matter what strategy node $j$ adopts (the term strategy and action are interchangeable used in this paper), incorporation is the best strategy for node $i$ if $p > c$, while no matter what strategy node $i$ adopts, incorporation is also the best strategy for node $j$. Therefore, action set $(I, I)$ is the unique Nash equilibrium in their interaction. However, it is not a very satisfying outcome, since (C, C) can give both nodes a higher payoff $(p-c, p-c)$ than $(I, I)$ strategy with payoff $(0, 0)$. It is the famous Prisoner’s Dilemma payoff matrix [21].

Definition: 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 is no other outcome [21].

Proposition 3.1 A effective cooperation stimulating system has a Nash equilibrium to be Pareto Optimal on cooperation strategy.
3.3.1 Game Theory Model for Reputation System

In the reputation system, most researchers proposed to adopt a reputation threshold value to distinguish the selfish nodes from the cooperative nodes. If the neighbor nodes are cooperative for the packet forwarding, the reputation values of these nodes are increased by the monitoring nodes. Otherwise, their reputation values will be reduced. If the reputation values of the selfish nodes are below a certain threshold, their routing requests will be refused by all other nodes. Regardless of their inherent problems in the system design, we mainly discuss the problems in the incentive strategies of these reputation based methods. If each node knows their current reputation value and wisely manipulate their packets transmission by randomly dropping packets travel through.

Table 2 shows the payoff matrix for reputation system, where

\[
(C_i, I_j) = \begin{cases} (-c, p) & \text{if } R_{ij} > m \\ (0, 0) & \text{if } R_{ij} \leq m \end{cases}
\]

\[
(I_i, C_j) = \begin{cases} (p, -c) & \text{if } R_{ij} > m \\ (0, 0) & \text{if } R_{ij} \leq m \end{cases}
\]

Proposition 3.2 Reputation game is Pareto Optimal.
From table 2, we can find that if the reputation value of one of a pair of nodes below a threshold, namely \( R_t \), the payoff value of these pair of nodes is \( (0,0) \). Therefore, the Nash equilibrium is at \( (C, C) \), and the game is Pareto Optimal. However, if a selfish node can manipulate its reputation value above the threshold value, that is, keep \( R_c \cdot PD > R_t \), the outcome of this game is still non-pareto-optimal with packets dropping rate as \( \frac{R_c - R_t}{R_c + R_t} \).

3.3.2 Game Theory Model for Price-based System

In the price system, the researchers use virtual cash as an incentive to encourage the cooperation between nodes in the system. The forwarding node can get benefit from the cooperative behavior in terms of virtual cash. However, the source nodes receive the service at the cost of paying virtual cash. The transmission requests will be rejected, if the nodes do not have enough cashes for the transmission. Therefore, a new payoff matrix for the price-based system can be builded. Table 3 shows the payoff matrix of a pair of interactive nodes. Between two nodes with transmission strategies \( (C, I) \), an uncooperative node gains some benefit in terms of self-resource consuming, it costs \( m \) for receiving other’s service. While, although the cooperative node will suffer from packet losing, it can earn a benefit \( m \) from forwarding. Table 3 shows the payoff matrix of price-based system, where

\[
(C_i, I_j) = \begin{cases} (-c + m, p - m) & \text{if } R_{ij} > m \\ (0, 0) & \text{if } R_{ij} < m \end{cases}
\]

\[
(I_i, C_j) = \begin{cases} (p - m, -c + m) & \text{if } R_{ij} > m \\ (0, 0) & \text{if } R_{ij} < m \end{cases}
\]

Theorem 3.3 Price-based game is Nash equilibrium with Pareto Optimal if the transmission cost \( c \), packet transmission benefit \( p \), cooperation benefit \( m \) should satisfied \( p > c \& m > c \) satisfy the relationship as

\[
\begin{cases} p - c > p - m \\ p - c > 0 \end{cases}
\]

therefore, \( p > c \& m > c \).

Therefore, according to the lemma 3.3, proposition 3.4 can be got.

Proposition 3.4 price-based game is Pareto Optimal if the price it earns is higher than its transmission cost and packet transmission benefit is also higher than its transmission cost.

However, although the price-based system can stimulate the node’s cooperation in the MANET, if a node accumulates a considerable virtual credits, it can still refuse to be cooperative until the credit is not enough. That is, the nodes can still manipulate their price to be a selfish node.

3.3.3 Game Theory Model for ARM System

In the ARM system, the incentive strategy combines the reputation system and price-based system. Reputation system is used to judge the cooperation degree of each node, based on which, the price is paid for the packets
Performance Evaluation

Since in reality, the interactions between neighbor nodes are multiple-moves games, the nodes can change their interaction strategies as they want. Therefore, in this section, the performance of ARM, reputation system, price-based system are evaluated with a Monte Carlo simulation. In the simulation, 100 nodes identical distributed in the system randomly meet and play a multiple-moves game. Points based on the payoff matrix are then totalled for all players in each strategy. The number of players for each strategy in the next round of games (generation) is simply the relative success of the strategy multiplied by the total number of players in the population. It is assumed that the population size stays constant and just the proportion of players in each strategy changes. The new player numbers are rounded to the nearest integer. In the system, although the cost for each transmission is different, without loss of generality, we assume that the normalize payoff for the transmission is 2, packet transmission benefit is 4 to compare the performance of reputation system, price based system and ARM. We also suppose the initial reputation value of each node is 1.0, the reputation threshold is 0.3. In the packet transmissions, every time when the nodes act cooperative, their reputations are increases by 0.1. Otherwise, reduced by 0.1. Initially, there are mixed of 50 cooperators and 50 defectors at the start.

Figure 1(a) shows the change of density of nodes in MANET with no cooperation incentive scheme. From the figure, we can find that after several interactions, the uncooperative nodes domain the population of the system. It is because in this scenario, the uncooperative strategy is the Nash equilibrium although it is not Pareto Optimal. Since the strategy of each node can change with each interaction, these self-interest nodes will no longer use cooperative strategy which bring them the safest and largest benefit.

Figure 1 (b) shows the change of density of nodes in MANET with reputation system. The figure indicates that before about 8 - 9 interactions, the uncooperative strategy is still the dominate strategy. It is because uncooperative strategy is still the Nash equilibrium before the reputation value of the nodes falls below the reputation threshold. Then since the selfish nodes are punished, cooperative strategy will be the Nash equilibrium at this time. Therefore, the selfish node should increase their reputation by taking cooperation strategy. However, after the reputation value increase above the threshold value, the uncooperative strategy become the Nash equilibrium again.

Figure 1 (c) shows the change of density of nodes in MANET with reputation system. The figure shows that the cooperative strategy is always being the Nash equilibrium.

<table>
<thead>
<tr>
<th>Table 4. Payoff matrix for ARM system</th>
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<tbody>
<tr>
<td><strong>Node i</strong></td>
</tr>
<tr>
<td><strong>Node j</strong></td>
</tr>
<tr>
<td>Cooperate</td>
</tr>
<tr>
<td>Incooperate</td>
</tr>
</tbody>
</table>

Theorem 3.5 ARM has a Nash equilibrium with Pareto Optimal if transmission cost \( c \), current reputation value \( R_j \) and \( R_i \), and cooperation benefit \( m \) satisfied \( \frac{m}{R_j} > c \& \frac{m}{R_i} > c \& \frac{m}{R_j} > c \& \frac{m}{R_i} > c \). 

Proof In order to have \((C, C)\) strategy to be the Nash equilibrium with Pareto Optimal, according to the “min-maximizing” method [21], the pay-off values should satisfy

\[
\begin{align*}
(p - c + \frac{m}{R_j} - \frac{m}{R_i}) - &> (p - c + \frac{m}{R_i} - \frac{m}{R_j}) \quad \text{if } (C_{r_i} > \frac{R_i}{R_j} \& \& C_{r_j} > \frac{R_j}{R_i}) \\
(p - c + \frac{m}{R_i} - \frac{m}{R_j}) - &> (p - c + \frac{m}{R_j} - \frac{m}{R_i}) \quad \text{if } (C_{r_j} > \frac{R_j}{R_i} \& \& C_{r_i} > \frac{R_i}{R_j}) \\
(\text{if } C_{r_i} > \frac{R_i}{R_j} \& \& C_{r_j} > \frac{R_j}{R_i}) - &> (p - c + \frac{m}{R_j} - \frac{m}{R_i}) \quad \text{if } (C_{r_j} > \frac{R_j}{R_i} \& \& C_{r_i} > \frac{R_i}{R_j}) \\%20c + \frac{m}{R_i} > 0 &> 0 \\
(\text{if } C_{r_j} > \frac{R_j}{R_i} \& \& C_{r_i} > \frac{R_i}{R_j}) - &> (p - c + \frac{m}{R_j} - \frac{m}{R_i}) \\
\text{therefore, } m &> c \cdot R_j \& \& c \cdot R_i \& \& c \cdot \frac{m}{R_j} \& \& c \cdot \frac{m}{R_i} > c.
\end{align*}
\]

From the payoff matrix we can find that even a node has a considerable amount of virtual credits, if it refuses to cooperate with other nodes, although the virtual 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 high virtual credits and less packets generating need can be prevented. Meanwhile, a low reputation value lead to a high price for the packet forwarding, therefore, its virtual credits will be quickly used up. Therefore, it is impossible for a node to manipulate a reputation value just below the threshold value.
Figure 1(d) shows the change of density of nodes in MANET with ARM. Since we give large payoff to the cooperative strategy and use node’s reputation values to prevent the node with less transmission request from being the selfish node, the nodes converge much faster to the cooperation strategy in ARM than the normal price based system.

5 Conclusions

In this paper, a hybrid system integrating the traditional reputation system and price-based system are evaluated based on the game theory models. Such system can effectively prevent the selfish nodes in traditional reputation system from manipulating their reputation value, and stimulate the selfish node with high number of virtual credits in traditional price based system to be cooperative with others. Simulation and analytical results show the high performance of the hybrid reputation system over the traditional typical system.

References