Analysis of packet relaying models and incentive strategies in wireless ad hoc networks with game theory

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Abstract

In wireless ad hoc networks, nodes are both routers and terminals, and they have to cooperate to communicate. Cooperation at the network layer means routing (finding a path for a packet), and forwarding (relaying packets for others). However, because wireless nodes are usually constrained by limited power and computational resources, a selfish node may be unwilling to spend its resources in forwarding packets that are not of its direct interest, even though it expects other nodes to forward its packets to the destination. In this paper, we propose a game-theoretic model to facilitate the study of the non-cooperative behaviors in wireless ad hoc networks and analyze incentive schemes to motivate cooperation among wireless ad hoc network nodes to achieve a mutually beneficial networking result.

1. Introduction

In a wireless ad hoc network, intermediate nodes on a communication path are expected to forward packets of other nodes so that nodes can communicate beyond their wireless transmission range. Typical examples of the wireless ad hoc networks include military communication or emergency response scenarios, where all participating nodes belong to the same authority, share a common goal, and are therefore motivated to act cooperatively to provide network services [1]. However, since wireless ad hoc networks are increasingly deployed in daily life scenarios such as inter-vehicle communication [2] and Internet access for remote areas [3], the participating nodes most unlikely belong to a single authority and no longer share a common goal any more. Cooperation in such networks cannot be assumed since it has been commonly accepted that network nodes in the above scenarios have the freedom to make decisions in their own best interests.

Since wireless nodes are usually constrained by limited power and computational resources, a selfish node may be unwilling to spend its resources in forwarding packets which are not of its direct interest, even though it expects other nodes to forward its packets to the destination. This is particularly true in typical wireless sensor network nodes [4], where battery-power is a scarce resource and forwarding is an energy-consuming network activity that will shorten a node's lifetime. Even in an ideal case in which nodes have no power and computational constraints, forwarding packets consumes a portion of bandwidth and processing time available to the forwarding nodes. Thus, the forwarding cost is not zero; a reasonable move for a node which does not belong to a central authority is to drop the packets belonging to any other node but itself, i.e., to act selfishly. In the worst case, assuming every node is selfish, this behavior will have a collective effect to bring down the communication mechanism of the whole ad hoc network, and result to a *tragedy-of-the-commons* [5].

2. Related work

Non-cooperative issues in ad hoc networks have drawn considerable attention over the past few years, and it has been shown that the presence of selfish nodes degrades the overall performance of a non-cooperative ad hoc network [6].

Ideally, incentives should be provided to motivate cooperation among wireless ad hoc network nodes to achieve a mutually beneficial networking result. In essence, participating nodes should be rewarded for cooperative behaviors and be punished for non-cooperative behaviors. The incentive schemes for packet forwarding in the literature basically fall into two categories, namely, trust-based schemes and price-based schemes.

Trust-based schemes use trustworthiness and reputation information in routing to enforce the

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cooperation among nodes. In [6], participating nodes are designed to perform monitoring to overhear the packet retransmission and avoid transmission to misbehaving nodes. CONFIDANT [7] distributes trustworthiness information among those participating nodes, and every node is supposed to keep a reputation list of the nodes with which it has previously interacted. A subjective logic trust model is proposed in [8] for the mapping between the evidence space and the trust space, and further applied to the trusted protocol for wireless ad hoc networks. This design is similar in [9], but with more technical details and quantitative analysis. More recent approaches, such as [10] and [11], evaluate the trust level of a node by aggregating feedback information from its neighbors to reduce the communication overhead. STRUDEL [12] is a distributed framework that tackles the problem of free-riders in Coalition Peering Domains by using a Bayesian trust model to dynamically select and isolate malicious peers.

Price-based schemes introduce services charges to the packet transmission process and usually use micro-payment to compensate the resource consumption incurred from the transmission. A virtual currency NUGLET [13] is introduced by L. Buttyan and J.-P. Hubaux as economic incentive. Each intermediate node buys a packet for some nuglets, and sells it to the next one for more nuglets. Therefore a node increases its nuglet amount during packet forwarding. SPRITE [14] applied the same idea, but with a credit based system and a central clearing banking service, to remove the need to carry real currency. A priced priority forwarding scheme was studied [15], in which a pricing mechanism allows the nodes to arbitrarily set the cost of priority forwarding of a packet. APE [16] is a virtual economy scheme to encourage the intermediate nodes to reveal the cost of packet forwarding, and thus to choose a cost-efficiency route. A general discussion about micro-payment schemes is available [17], but is not specific to wireless ad hoc networks.

Though a node's behaviors in wireless ad hoc networks mirror a real world decision making process, game theoretic models and designs have not been explored much in the wireless ad hoc networks literature. In [18], V. Srinivasan et al. proposed a game playing strategy to achieve a Nash equilibrium that converges to the rational and Pareto optimal. The fairness issue was studied in [19] for bandwidth allocation in ad hoc networks and a game theoretic model for intrusion detection in wireless ad hoc networks was discussed in [20]. A survey on applying game theory to wireless ad hoc networks is available [21]. Some of the basic analysis of forwarding in single-stage and repeated-game scenarios can be founded on [26], [27], [28]. However, the existing works are either not explicit or too general. In this paper, we propose a formal action model of wireless ad hoc network nodes based on game theory. Since all nodes have to periodically choose an action (e.g. forwarding or dropping), this is a repeated game for all the participants. Because of the complexity of the problem, we restrict our analysis to a static network scenario in this paper.

3. Overview of the game theoretic model

Let us first consider the simplest forwarding scenario which consists of two nodes i and j, where i wants j to forward a packet to other nodes. We will study a more complex model later. The denotations used in the following discussions are summarized in Table 1.

Table 1. Denotation list

Symbol	Meaning
r	reward
s	resource
b	benefit
t	time
d	discount rate
f	forward probability
$-i$	node's opponent
g	forgiveness component
h	tolerance threshold

4. The single-stage game

We assume that j has freedom to decide whether to forward or drop the packet. We also assume there is a reward mechanism such that for each successful forwarding, i will get its reward of value r for enforcing j to forward packets; and meanwhile, j will consume its resource of value s to complete the forwarding.

Further, we define the interaction model between nodes as bi-directional, i.e., while j transmits i's packet, i shall transmit j's packet simultaneously. Since bi-directional wireless communication is never physically simultaneous, this setting has implication on the physical layer in which the two transmissions in one interaction should be independent, i.e., nodes should make decisions on forwarding or dropping at the same time.

We can see the above scenario is a single stage prisoner's dilemma [22], where the motivation for a node to participate in this game playing is to maximize its benefit and the action it can take is to decide whether to forward or drop. For this game, the benefits accrued by each node for every strategy profile are tabulated in Table 2.

In this typical single stage prisoner's dilemma, the best strategy for a participating node is to drop the packet, since this action will maximize its benefit. We can further prove that mutual dropping will lead to Nash equilibrium: since the benefit function of each node is monotonically increasing with dropping actions and the maximized benefit of a node is r, dropping is a dominating strategy in this case. In other words, no node can gain more profit by cooperation with others. Putting into the wireless ad hoc networking context, it implies that selfish actions are actually encouraged but this will lead to zero throughput of the whole network.

Table 2. Benefit vs. Strategy

	Forward	Drop
Forward	*r-s, r-s*	*-s, r*
Drop	*r, -s*	*0, 0*

5. The repeated game

If the packet forwarding game is played only once, there is no way we can achieve cooperation among these participating nodes; but in a real world setting, all nodes have to periodically choose an action (e.g. forwarding or dropping), and it becomes a repeated game for all the participating nodes. Similarly to the single stage game above, it achieves a non-optimum equilibrium when played repeatedly; however, sub-optimum equilibriums are achievable, provided that players do not know a priori how many repetitions of the game there will be.

Since a repeated game is path-dependent, a node has to take consideration of the present action's impact on its future consequence [23]. We extend our previous model to reflect the impact of past event on future actions: assume that time *t* is discrete and divided in frames like $t_1, t_2, \ldots, t_n$. A node *i* will make a decision at each stage t_n of the game, but its benefit gained at each stage will be discounted by a rate at *d* to reflect a past action's impact factor over time [24]. In the extreme case $d = 0$, it means the players are short-sighted and the game degrades into a single stage one.

Table 3. Probability of node $i_{t=t_n}$ to forward upon observing $\{i, j\}_{t=t_{n-1}}$

i \ *j*	Forward	Drop
Forward	1	$\dfrac{r/s-1/d}{r/s-1}$
Drop	$\dfrac{1/d-1}{r/s-1}$	0

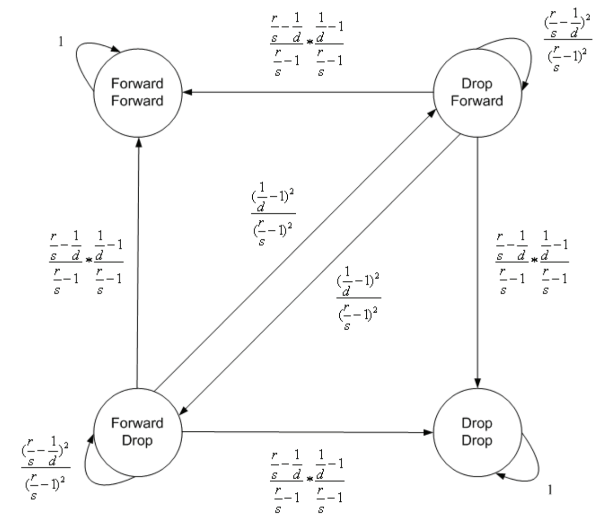

Figure 1. Probability of state transitions

We consider the simplest situation where the repeated game is memory-less, i.e. a player *i* at a time frame t_n will choose an action only according to the previous situation at the time frame t_{n-1}. If we limit the action profile as a set {*Forward*, *Drop*} and map the action selection process as a state transition process, a series of states of participating nodes constitute a Markov chain [25]. At each time a node may have changed from the state it was in the moment before, or it may have stayed in the same state. In the above setting, the participating nodes are playing the packet forwarding game by changing states (i.e. transitions).

Applying the probability-based winning strategy stated in [23], we tabulate a sub-optimum action profile in Table 3 where a node *i* at a time frame t_n shall change states to maximize its benefits by observing the state $\{i, j\}$ at the time frame t_{n-1}. A state transition chart in Figure 1 is drawn based on Table 3, where each state is mapped to a combination of nodes' action profile $\{i, j\}$. The transition probability between states is labeled accordingly.

Let us analyze a node's dynamic behaviors in the above settings: (1) the states {*Forward*, *Forward*} and {*Drop*, *Drop*} are stable ones. At the bootstrapping stage, if two nodes initially interact by forwarding each other's packets, this cooperation will be encouraged and most likely to continue. On the contrary, if two nodes are not cooperative at the first point, a future cooperation is most unlikely. (2) the states {*Forward*, *Drop*} and {*Drop*, *Forward*} are transient ones. A node may find itself in those states at the bootstrapping stage if one of them decides to cooperate while the other not, or at a later stage if a node takes a wrong decision and swerves from the stable states. In this situation, a node will continue to forward with a positive probability, which ensures a potential that a future stable state {*Forward*, *Forward*} may be reached. The consequence of reaching {*Forward*, *Forward*} can therefore be deemed as a reward for forwarding packets, and the consequence of reaching {*Drop*, *Drop*} as a punishment for dropping packets.

6. The probability game

We now consider a more general model. A participating node in this game takes actions by adjusting its attitude towards forwarding. Explicitly, we denote a node's probability of forwarding a packet as *f*, where in this case $f=0$ means dropping all the requested packets and $f=1$ means forwarding all the requested packets. Let *i* denote the playing node's id and –*i* denote its opponent, the benefit of a node for playing this game at a time frame t_n is $b_i^{t_n} = f_{-i}^{t_n} r - f_i^{t_n} s$. The final benefit of a node finishing the game is $B_i = \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s)$, where *d* is the discount rate. We study several classical strategies [23] and their sub-optimum equilibrium conditions.

6.1. Tit-For-Tat

TFT (Tit For Tat) is a highly effective strategy in game theory for the iterated prisoner's dilemma [23]. A player using this strategy will initially cooperate, and then respond in kind to an opponent's previous action. If the opponent previously was cooperative, the player is cooperative. If not, the player is not. We model the TFT strategy as follows:

$$f_i^{t_n} = \begin{cases} 1, & n = 0 \\ f_{-i}^{t_{n-1}}, & n > 0 \end{cases} \tag{1}$$

TFT provides incentives to cooperate since one player's present move will have impact on its future consequence. Let's study the node dynamics in this strategy.

Assume all participating nodes are adopting TFT at the bootstrapping stage. It is obvious that this cooperation will continue as the forwarding probability will remain 1 and thus all packets will be forwarded. If at some point a node *i* unilaterally changes its forwarding probability to $f_i^{t_0} = p$ (e.g. due to a physical transmission failure), its opponent will copy its behavior and set its forwarding probability to $f_{-i}^{t_1} = p$; but the node *i* itself follows its opponent's previous behavior, thus its own forwarding probability will be set back to $f_i^{t_1} = 1$. The above process will continue repeatedly and in the end we will see an alternate changing sequence as follows:

$$\begin{aligned} f_i^{t_n} &= \{p,\ 1, p,\ 1,\ \cdots\} \\ f_{-i}^{t_n} &= \{1, p,\ 1, p,\ \cdots\} \end{aligned} \tag{2}$$

We can calculate the final benefit to node *i* of playing this game:

$$\begin{aligned} B_i &= \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s) \\ &= [(r - ps) + d(pr - s)] * (1 + d^2 + d^4 + \cdots) \\ &= \frac{(r - ps) + d(pr - s)}{1 - d^2} \end{aligned} \tag{3}$$

A node will adopt this strategy if and only if it will gain profit from it, i.e. $B_i \geq 0$. We solve Equation 3 and derive the boundary condition as:

$$\frac{r}{s} \geq \frac{d + p}{1 + dp} \tag{4}$$

6.2. Generous Tit For Tat

It is easily shown that TFT has no recovery mechanism for rebuilding cooperation. If a node unintentionally degrades its forwarding probability to $0 \le f < 1$, there is no way to recover the cooperation to the original level. We can also show that if the degradation process continues, i.e. $f_i^{t_n} < f_i^{t_m}$ where $n > m$, the cooperation level will in the end degrade to $\min(f_i^{t_n}, f_{-i}^{t_m})$ where $0 \le n \le N$ and $0 \le m \le N$. In order to rebuild cooperation, a natural way is to add some *forgiveness* elements to the strategy.

GTFT (Generous Tit For Tat) is a variety of TFT with a forgiveness component [23]. Similar to TFT, a player using this strategy will initially cooperate, and then respond in kind to an opponent's previous action. If the opponent previously was cooperative, the player is cooperative. If not, the player is not. The difference between GTFT and TFT lies in how to deal with non-cooperative behaviors: in GTFT, a forgiveness component g is added to the player's response. We model the GTFT strategy as follows:

$$f_i^{t_n} = \begin{cases} 1, \ n = 0 \\ \min(f_{-i}^{t_{n-1}} + g, \ 1), \ n > 0 \end{cases} \tag{5}$$

We will now discuss the sub-optimum equilibrium condition for GTFT. Suppose all nodes are adopting GTFT at the bootstrapping stage, and the cooperation continues until some point when a node *i* unilaterally changes its forwarding probability to $f_i^{t_0} = p$. Depending on the degree of deviation, its opponent will respond with GTFT: (1) a slight degree of deviation, i.e., $p \ge 1 - g$, will be tolerated, and it will still forward all packets; (2) a bigger deviation, i.e. $p < 1 - g$, is deemed non-cooperation, and it will adjust its forwarding probability to $p + g$. The rest process will continue repeatedly, similar to TFT. If we consider the worst case $p < 1 - g$, an alternate changing sequence will appear as follows:

$$\begin{aligned} f_i^{t_n} &= \begin{cases} \min(p + ng, \ 1), \ \mathrm{mod}(n, \ 2) = 0 \\ 1, \ \mathrm{mod}(n, \ 2) = 1 \end{cases} \\ f_{-i}^{t_n} &= \begin{cases} 1, \ \mathrm{mod}(n, \ 2) = 0 \\ \min(p + ng, \ 1), \ \mathrm{mod}(n, \ 2) = 1 \end{cases} \end{aligned} \tag{6}$$

The above sequence will converge to $\{\cdots, 1, 1, 1, \cdots\}$, given an enough long time. It implies that the cooperation can be rebuilt over time in GTFT. We can further derive the recovery point $t_{n'}$ at

$$n' = \left\lceil \frac{1-p}{g} \right\rceil + n \tag{7}$$

From Equation 7 we can see if the forgiveness component g is sufficiently large, the system will quickly recover to the full cooperation state.

We then calculate the final benefit to node *i* of playing this game:

$$\begin{aligned} B_i &= \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s) \\ &= [(r - ps) + d(pr - s)](1 + d^2 + d^4 + \cdots) \\ &\quad + gd(r - 2ds + 3d^3 r - 4d^4 s + \cdots) \end{aligned} \tag{8}$$

If we solve the Equation 8 with $B_i \ge 0$, we shall be able to derive the boundary condition for a node to apply this strategy.

So far we have studied two linear strategies TFT and GTFT, where punishments are liner to misbehaviors. We will then discuss two more non-linear strategies, e.g. trigger strategies, where punishments are non-linear to misbehaviors.

6.3. Grim Trigger

Grim Trigger (GT) is a trigger strategy in game theory for a repeated game [23]. Initially, a player using GT will cooperate, but as soon as the opponent defects (thus satisfying the trigger condition), the player using GT will defect for the remainder of the iterated game.

Since a single defect by the opponent triggers defection forever, GT is the most strictly unforgiving of strategies in an iterated game. The implication in the network design is that once a node misbehaves, it will be isolated permanently. We model GT as follows:

$$f_i^{t_n} = \begin{cases} 1, \ n = 0 \\ 1, \ \forall m < n : f_{-i}^{t_m} \ge h \text{ and } n > 0 \\ 0, \text{ all else} \end{cases} \tag{9}$$

where h is introduced as the tolerance threshold and the trigger condition is $f < h$.

We will then discuss the sub-optimum equilibrium condition for GT. Suppose all nodes are adopting GT at the bootstrapping stage, and the cooperation continues until some point when a node i unilaterally changes its forwarding probability to $f_i^{t_0} = p$. Depending on the degree of deviation, its opponent will respond with GT: (1) a slight degree of deviation, i.e., $p \geq h$, will be tolerated, and it will still forward all packets; (2) a bigger deviation, i.e. $p < h$, will trigger the punishment, and it will from now on drop all the packets forever. If we consider the worst case $p < h$, the forwarding probability sequence will be:

$$\begin{aligned} f_i^{t_n} &= \{p,\ 1, 0, 0, \cdots\} \\ f_{-i}^{t_n} &= \{1,\ 0, 0, 0, \cdots\} \end{aligned} \tag{10}$$

Let us calculate the final benefit to node i of playing this game:

$$\begin{aligned} B_i &= \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s) \\ &= r - ps - ds \end{aligned} \tag{11}$$

Using the condition $B_i \geq 0$, we get the boundary condition for a node to apply this strategy:

$$\frac{r}{s} \geq d + p \tag{12}$$

6.4. One-step Trigger

It is obvious that GT has no recovery mechanism for rebuilding cooperation, either. If a node unintentionally degrades its forwarding probability to $f < h$, there is no way to recover the cooperation to the original level; from then on, the degradation process will continue as well and it will quickly converge to $f = 0$, i.e. a fully non-cooperative state.

OT (One-step Trigger) is an improvement to GT with a milder punishment [23]. Similar to GT, a player using OT will initially cooperate, but once the opponent defects (thus satisfying the trigger condition), the player using OT will defect once, but then it is immediately ready to re-establish cooperation. We model OT as follows:

$$f_i^{t_n} = \begin{cases} 1,\ n = 0 \\ 1,\ f_{-i}^{t_{n-1}} \geq h \text{ and } n > 0 \\ 0,\ \text{all else} \end{cases} \tag{13}$$

where h is the tolerance threshold and the trigger condition is $f < h$.

Let us discuss the sub-optimum equilibrium condition for OT. Suppose all nodes are adopting OT at the bootstrapping stage, and the cooperation continues until some point when a node i unilaterally changes its forwarding probability to $f_i^{t_0} = p$. Depending on the degree of deviation, its opponent will respond with OT: (1) a slight degree of deviation, i.e., $p \geq h$, will be tolerated, and it will still forward all packets; (2) a bigger deviation, i.e. $p < h$, will trigger the punishment; and it shall punish the opponent by dropping all packets at the time frame t_n. Unlike GT, it will re-examine its opponent's behavior at the next time frame t_{n+1}, and apply the above rules again. If we consider the worst case $p < h$, the forwarding probability sequence will be:

$$\begin{aligned} f_i^{t_n} &= \{p,\ 1, 0, 1, 0, 1, \cdots\} \\ f_{-i}^{t_n} &= \{1,\ 0, 1, 0, 1, 0, \cdots\} \end{aligned} \tag{14}$$

We now calculate the final benefit to node i of playing this game:

$$\begin{aligned} B_i &= \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s) \\ &= (r - ds)(1 + d^2 + d^4 + \cdots) - ps \\ &= \frac{r - ds}{1 - d^2} - ps \end{aligned} \tag{15}$$

With the condition $B_i \geq 0$, we derive the boundary condition for a node to apply this strategy:

$$\frac{r}{s} \geq d + (1 - d^2)p \tag{16}$$

7. Analysis with the model

So far we have not yet compared different strategies. In order to evaluate the pros and cons of those strategies, a benchmark is needed. Ideally, a fully cooperative status is such a situation that all packets are forwarded without exceptions. We may take this as the benchmark for our discussion. Thus we model the FC (Fully Cooperative) strategy as follows:

$$f_i^{t_n} = f_{-i}^{t_n} = \{1,\ 1,\ 1,\ \cdots\} \tag{17}$$

We calculate the final benefit to node i of playing this game:

$$\begin{aligned} B_i &= \sum_{n=0}^{\infty} d^n (f_{-i}^{t_n} r - f_i^{t_n} s) \\ &= (r - s) * \sum_{n=0}^{\infty} d^n \end{aligned} \tag{18}$$

Let $B_i \geq 0$, we derive the boundary condition for a node to apply this strategy:

$$\frac{r}{s} \geq 1 \tag{19}$$

We summarize the boundary conditions for the above strategies in Table 4. In conclusion, the results from Table 4 imply that cooperation can be achieved in a network of selfish nodes, given network parameters (e.g., earning-cost ratio) carefully designed.

Besides, network fluctuations and measurement errors may trigger unjust punishments, and those punishments may have irrevocable future effects in some strategies; in designing a practical strategy for real world networking, recovery mechanism shall be taken into serious considerations.

8. Concluding remarks

In this paper, we have proposed a game theoretic model to investigate the conditions for cooperation in wireless ad hoc networks. Because of the complexity of the problem, we have restricted ourselves to a static network scenario. The main finding is that a cooperative state in a network of selfish nodes without a central authority is theoretically achievable, given network parameters (e.g. cost-earning ratio, discount rate, tolerance threshold, etc) carefully designed.

We have then studied different node strategies within this model, and derived boundary conditions of cooperation for those strategies. It is our hypothesis that an optimal strategy should bear at least the following merits:

--It is good (it starts by cooperating)

--It is retaliating (it returns the opponent's defection)

--It is generous (it forgets the past if the defecting opponent cooperates again)

--It is not memoryless (it utilizes the history information).

Table 4. Comparison of strategies

Strategy	Boundary Condition	Recovery Mechanism
TFT	$\frac{r}{s} \geq \frac{d+p}{1+dp}$, where $0 \leq p \leq 1$	No
GTFT	*	Yes
GT	$\frac{r}{s} \geq d + p$, where $0 \leq p < h \leq 1$	No
OT	$\frac{r}{s} \geq d + (1-d^2)p$, where $0 \leq p < h \leq 1$	Yes
FC	$\frac{r}{s} \geq 1$	N.A.

[a]Take a different form than others. See Section 6.2 for details.

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