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A game theory based reputation mechanism to incentivize cooperation in wireless ad hoc networks ☆

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ABSTRACT

In wireless ad hoc networks one way to incentivize nodes to forward other nodes' packets is through the use of reputation mechanisms, where cooperation is induced by the threat of partial or total network disconnection if a node acts selfishly. The problem is that packet collisions and interference may make cooperative nodes appear selfish sometimes, generating unnecessary and unwanted punishments. With the use of a simple network model we first study the performance of some proposed reputation strategies and then present a new mechanism called DARWIN (Distributed and Adaptive Reputation mechanism for Wireless ad hoc Networks), where we try to avoid retaliation situations after a node is falsely perceived as selfish to help restore cooperation quickly. Using game theory, we prove that our mechanism is robust to imperfect measurements, is collusion-resistant and can achieve full cooperation among nodes. Simulations are presented to complement our theoretical analysis and evaluate the performance of our algorithm compared to other proposed reputation strategies.

1. Introduction

Wireless ad hoc networks consist of a set of self-configuring nodes that do not rely on any infrastructure to communicate among each other. To achieve this goal, a source communicates with a distant destination through intermediate nodes that act as relays. It is usually assumed that in such networks, nodes are willing to cooperate forwarding packets, but this assumption is not necessarily true in the case where all nodes are not under the control of a single authority. In these cases, there can be selfish nodes that want to maximize their own welfare without regard to social welfare, where we define a node's welfare as the benefit of its actions minus the cost of its actions. In such scenarios, cooperation cannot be taken for granted and therefore, it is necessary to develop mechanisms that allow cooperation to emerge even in the presence of selfish users.

Incentive mechanisms can be broadly divided in two categories: credit-exchange systems and reputation-based systems. In credit-exchange systems [2–8], cooperation is induced by means of payments received every time a node acts as a relay and forwards a packet, and such credit can later be used by these nodes to encourage others to cooperate. To guarantee that nodes do not counterfeit payments, some strategies rely on the use of tamper-proof hardware to store credit and guarantee the check and balances, but this strategy may hinder their ability to find wide-spread acceptance; other strategies rely on the presence of an off-line central trusted authority which may be hard to guarantee in some scenarios. In reputation-based strategies [9–17], a node's behavior is measured by other nodes in the network. Selfish behavior is then discouraged by the threat of partial or total network disconnection. The problem is that due to interference and collisions it is not always possible to perfectly estimate how a node behaves,

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so sometimes cooperative nodes are perceived as being selfish and punished accordingly; such scenarios can lead to retaliation situations that may potentially decrease the throughput of cooperative nodes.

The contributions of this paper are twofold: first, we use a simple game-theoretic network model to study the robustness of some previously proposed reputation-based strategies. We show that some strategies are not self-enforcing, meaning that there is an incentive to deviate from the expected behavior, while others punish selfish behavior at the expense of the throughput of cooperative nodes, potentially leading to complete network disconnection due to retaliation. Second, we propose a new strategy called DARWIN (Distributed and Adaptive Reputation mechanism for WIreless ad hoc Networks) that effectively detects and punishes selfish behavior. We derive conditions under which no node can gain from deviating from our strategy, prove that full cooperation can emerge among nodes, and that our scheme is collusion-resistant.

Simulations are also presented to complement the theoretical contributions. Our results show that the throughput achieved with DARWIN is better than any of the other strategies studied, and that DARWIN can be implemented with low overhead.

The rest of the paper is organized as follows. Section 2 introduces some concepts from game theory that are used in this paper. In Section 3 we define the network model which will be used in Section 4 to analyze some of the previously proposed strategies. We introduce our strategy in Section 5, analyze the conditions under which cooperation can emerge, study its performance, and show that it is relatively insensitive to parameter choices. The impact of collusion among nodes is also studied there. Section 6 presents the results of a simulation-based study of DARWIN and how it compares to other reputation-based strategies. Section 7 presents an overview of related work. Finally, Section 8 presents the conclusions.

2. Basic game theory concepts

Here we introduce the concepts from game theory [18] that are used in this paper. As an illustration, we use a well-known game between two players known as *The Prisoners' Dilemma*. Both players have two possible *pure strategies*, Cooperate (C) or Defect (D), and the payoffs they receive for their actions are given in Table 1. Then player i's *strategy space* S_i is defined to be the set of pure strategies available to it. In this case $S_i = \{C, D\}$ for $i = \{1, 2\}$. A *strategy profile* is defined to be an element of the product-space of strategy spaces of each player. An example is for player 1 to play D and player 2 to play C.

Table 1
Payoff matrix of the Prisoners' Dilemma game.

	Player 2			
	Cooperate		Defect	
Player 1				
Cooperate	1	1	−1	2
Defect	2	−1	0	0

Definition 1. A *Nash equilibrium* is a strategy profile having the property that no player can benefit by unilaterally deviating from its strategy.

Such a strategy profile is considered to be *self-enforcing*. In this example, the Nash equilibrium would be the strategy profile $s = (D, D)$. Assume now that this game is repeated infinitely many times, and for each k, the outcomes of the $k-1$ preceding plays are observed before the kth stage begins. In this case, the total payoff of the game for player i is the discounted sum of the stage payoffs. Denoting the stage payoffs by $u_i^{(k)}$, the total payoff is given by

$$U_i = \sum_{k=0}^{\infty} w^k u_i^{(k)},$$

where $w \in (0, 1)$ is the *discount factor*. The infinitely repeated game can also be interpreted as a repeated game that ends after a random number of repetitions. Under this interpretation, the length of the game is a geometric random variable with mean $1/(1-w)$.

In this game a player's strategy specifies the action it will take at each stage, for each possible history of play through previous stages. In our example a strategy for player 1 could be to cooperate until player 2 defects, and then defect forever. Since both players know the previous history, we can view the game starting at stage k with a given history h^k as a new game; this is called a *subgame* of the original game.

Definition 2. For a given set of strategies that are in Nash equilibrium, history h^k is *on the equilibrium path* if it can be reached with positive probability if the game is played according to the equilibrium strategies, and is *off the equilibrium path* otherwise.

Definition 3. A Nash equilibrium is *subgame perfect* if the player's strategies constitute a Nash equilibrium in every subgame.

Subgame perfection is a stronger concept that eliminates *noncredible* equilibria, since it analyzes the case when a game is on or off the equilibrium path. This will later help us analyze whether a given reputation scheme is robust enough to handle the case when due to inaccurate measurements nodes appear to be out of their predicted behavior.

Definition 4. A game is *continuous at infinity* if for each player i the payoff U_i satisfies:

$$\sup_{h,\tilde{h} \ s.t. \ h^k = \tilde{h}^k} |U_i(h) - U_i(\tilde{h})| \to 0 \ as \ k \to \infty.$$

Under this definition, events in the distant future are relatively unimportant. This holds true if the total payoff of the game is the discounted sum of the per-period payoffs $u_i^{(k)}$, and the per-period payoffs are uniformly bounded. In our example this holds true since $u_i^{(k)} \leqslant 2$ for all k.

Lemma 1. One-Stage Deviation Principle *In an infinite-horizon multi-stage game with observed actions that is continuous at infinity, strategy profile s is subgame perfect if*