Addressing Forwarder's Dilemma: A Game-Theoretic Approach to Induce Cooperation in a Multi-hop Wireless Network

Saswati Mukherjee[1], Sreya Dey[2], Rajdeep Mukherjee[2], Matangini Chattopadhyay[1], Samiran Chattopadhyay[2], and Debarshi Kumar Sanyal[2]

[1] School of Education Technology, Jadavpur University, India
[2] Department of Information Technology, Jadavpur University, India
sash_cal@rediffmail.com,
{this.is.sreya07,thekoolrajdeep,debarshisanyal}@gmail.com,
chttpdhy@yahoo.com, samiranc@it.jusl.ac.in

Abstract. Nodes in a multi-hop wireless network often have limited or constrained resources. Therefore, to increase their lifetime, intermediate nodes are often unwilling to forward packets for other nodes, thereby decreasing network throughput. Thus, some mechanism has to be designed which prevents the nodes from adopting such selfish behavior. In this paper, we suggest a scheme using game theory to induce such cooperation. The nodes are the players and their strategies are their packet forwarding probabilities. We design novel utility functions to capture the characteristics of packet forwarding dilemma. We then set up simulations to analyze the Nash equilibrium points of the game. We show that cooperation in multi-hop communication is feasible at the operating point if the costs of packet forwarding are not too high.

Keywords: Forwarder's dilemma, Nash equilibrium, Wireless networks, Performance.

1 Introduction

A multi-hop wireless network is a collection of computers and devices (*nodes*) connected by wireless communication *links*. Because each radio link has a limited communications range, many pairs of nodes cannot communicate directly, and must forward data to each other via one or more cooperating intermediate nodes.

Multi-hop communication is not an issue where nodes are altruistic and faithful to a global algorithm. However, if nodes are selfish, they may not behave cooperatively as they have an incentive to *free-ride* by sending their own packets without relaying packets for others since relaying packets for others consumes bandwidth and energy. This concentrates traffic through the cooperative nodes, which decreases both individual and system throughput, and might even partition an otherwise connected network.

Hence, the need arises to design some mechanism that induces cooperation among the nodes. The basic aim of any such mechanism is to encourage the nodes to forward

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packets sent to it by other nodes. This can be done in a positive or a negative way, that is, a node can be made to cooperate within a network either by providing some incentive or by taking penalty actions against a node when its rate of packet forwarding falls below a particular value. Marti et al. [10] discuss schemes to identify misbehaving nodes (non-forwarders) and deflect traffic around them. Michiardi and Molva [8] devise reputation mechanisms where nodes observe the behavior of others and prepare reputation reports that they use to behave selectively. Zhong et al. [9] propose the use of currencies to enforce cooperation. Buttyan and Hubaux [5, 6] devise a scheme based on a virtual currency called a *nuglet* that a node pays to send its own packets but receives if it forwards other's packets. Cooperation without incentive mechanisms is an interesting topic. Srinivasan et al. [11] and Urpi et al. [1] study the same in general mathematical frameworks. In [7], Felegyhazi et al. use game theoretic and graph theoretic notions to examine whether cooperation can exist in multi-hop communication without incentive mechanisms. They consider the effect of network topology and communication patterns on the cooperative behavior. In [3], the authors propose a self-learning repeated game framework to enforce cooperation in wireless ad hoc networks. In [2], Kamhoua et al. model packet forwarding as a stochastic game in which each node observes the behavior of its neighbours using an imperfect monitoring technology. They develop a strategy that constrains self-interested nodes to cooperate under noise.

In this paper, we propose a model in which the problem of forwarder's dilemma can be modeled using non-cooperative game theory [4]. In this framework, the nodes must choose their behavior, regarding packet forwarding, that is, they have to make decisions every time a packet is sent to them for forwarding. We use a game theoretic model to study this scenario. The strategy of a node is the probability with which it forwards a received packet. Note that this is a generalization of the binary choices of dropping or relaying a packet to a continuous space. The utility function of a node is the point awarded to it by the base-station (based on its forwarding actions) offset by the cost incurred in forwarding. A selfish rational node attempts to maximize its utility function. The natural solution of the game is a Nash equilibrium.

We show the existence of Nash equilibria in the game. We use different criteria to select the desirable equilibria and show that cooperation is feasible. The novelty of our work lies in identifying utility functions that model the situation in an elegant way and ensuring the existence of desirable Nash equilibria in the game. Unlike many other works we do not use explicit currencies. Also we use refined notions of Nash equilibrium that boost the performance of the network as a whole.

The remainder of this paper is organized in the following manner. Section 2 discusses the features of our model. The results obtained are enumerated in section 3 and the inferences are drawn in section 4.

2 Model Definition

In this section, we give a formal definition of the proposed model and the reasons why we have chosen this model. Since we are studying cooperation in packet forwarding, we assume that the main reason for packet losses in the network is the non-cooperative behavior of the nodes.

Let us consider a wireless network having N nodes. Let **X** denote the set of nodes, where $\mathbf{X} = \{x_1, x_2 \ldots x_N\}$.

Each node in the network, in addition to its own packets, has to forward some packets for other nodes, in case it is an intermediate node between the source and the destination. However, due to the energy constraints of the nodes, there is a probability associated with the event of a node forwarding packets sent by other nodes. We denote this probability for a node x_i as p_i .Thus, if p_i is 1, a node definitely forwards the received packet. A value of p_i=0 indicates that the node drops the packet.

Let us assume the cost incurred by a node x_i in forwarding a packet is c_i. The cost can be defined to be the power consumed to transmit the packet, or the bandwidth occupied by the packet and so on. Let us assume that $0 < c_i < 1$.

In order to encourage nodes to forward packets, the base station gives each node x_i an incentive g_i that depends on the probability p_i with which the node forwards the packet. (We assume that the base station can collect all the required information.)

The whole scenario is defined as a non-cooperative game. Here the players are the nodes of the network and each node aims to maximize its payoff. The strategy set of each node is its set of allowable forwarding probabilities which is a closed subset of [0, 1]. We can define the utility of a node x_i, having a forwarding probability p_i as follows:

$$U_i(p_i) = g_i - p_i(1 - \prod_{i+1}^{d} p_j) - p_i^{1/\alpha} c_i \quad (1)$$

where $g_i = \ln(1 + p_i)$.

Note that the first term above is the incentive awarded by the base station. The second term refers to the probability that the packet does not reach the destination d given that this node has forwarded the packet. In this case, since the packet has not reached the destination, this node's forwarding action does not produce any benefit to the network. Each node that forwards a packet that does not actually reach the destination get a mild punishment for resource wastage. In practice, this could motivate the nodes to identify rogue nodes and refuse to forward their packets. However, such analysis is beyond the scope of the current work. The third term is the cost incurred in forwarding.

Substituting the value of g_i in (3.1) we get,

$$U_i(p_i) = \ln(1 + p_i) - p_i(1 - \prod_{i+1}^{d} p_j) - p_i^{1/\alpha} c_i \quad (2)$$

where, α is a constant that denotes the degree of cost-constraint of a node. Greater the value of α, more stringent a node is regarding forwarding packets for other nodes.

For simplicity, we assume that in this case, the value of α is 1.Therefore,

$$U_i(p_i) = \ln(1 + p_i) - p_i(1 - \prod_{i+1}^{d} p_j) - p_i c_i \quad (3)$$

Since the strategy set of each node is a closed subset of [0, 1], it is a closed bounded set which is compact and convex. Also, double differentiating equation (3.3) with respect to p_i, we get,

$$\frac{\partial_2 u_i}{\partial p_i^2} = -\frac{1}{(1+p_i)^2} < 0$$

Hence u_i is quasi-concave with respect to the strategy.

Thus, we can say that **there is at least one Nash Equilibrium point for the above game**. Recollect that a *Nash equilibrium* is an action profile $\mathbf{p}^* \in \mathbf{P}$ with the property that for all players $i \in$ N:

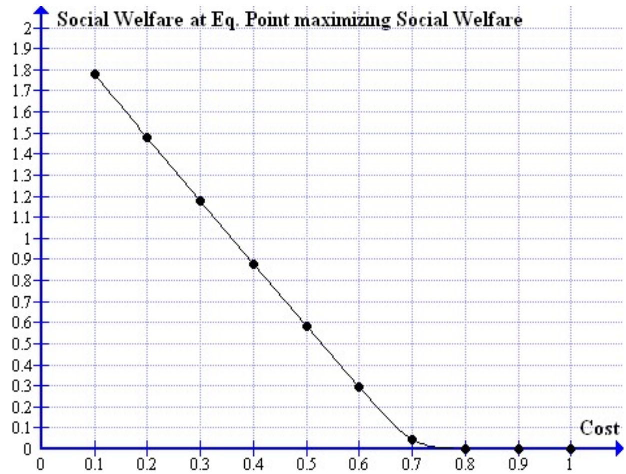
$$u_i(\mathbf{p}^*) = u_i(\mathbf{p}^*_{-i}, p^*_i) \bullet u_i(\mathbf{p}^*_{-i}, p_i) \; \forall \, p_i \in P_i$$

3 Nash Equilibria and Simulations

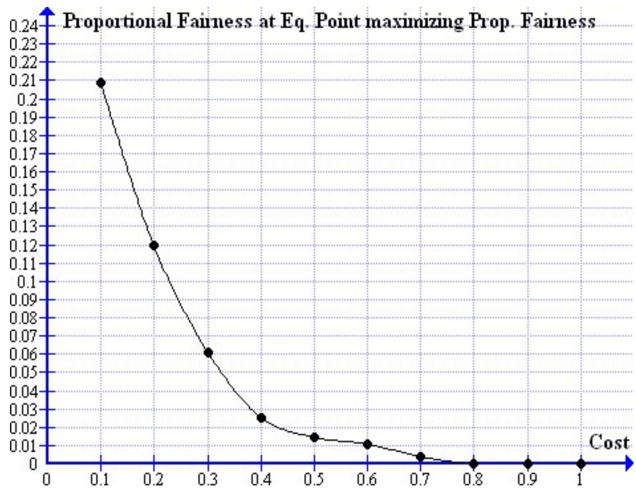
In the last section, we did not answer how many Nash equilibria are possible in the game. Indeed many Nash equilibria are possible (as we found out through simulations). So we define some refinements of the equilibrium so that only those that satisfy the refinement criteria are retained and the rest are filtered out. The two criteria we use to select the Nash equilibria are social welfare maximization and proportional fairness maximization. We choose those equilibria that maximize social welfare or maximize proportional fairness. Social welfare is the sum total of the payoffs of the n nodes that is, $\sum_{i=1}^{n} U_i$. A payoff profile is said to be proportionally fair if the products of the individual payoffs, that is, $\prod_{i=1}^{n} U_i$ is maximized.

We perform a simulation with 5 nodes in a chain topology, where the third node has a very high cost (=1) of packet forwarding with respect to the other nodes which have been considered equivalent in terms of their respective costs of packet forwarding. Each of these nodes has a cost of 0.1. We find that 92 Nash equilibria exist in this case. We select the case where nodes select the strategies that maximize social welfare and find that at Nash equilibria, the probability of packet forwarding for the third node is 0.98 while all the other nodes forward packets with a probability of 1. We obtain a social welfare of 2.03568 under this strategy set.

We consider the same topology again but now all nodes have the same forwarding cost. Graph 1 represents the value of the social welfare at the Nash equilibrium point maximizing social welfare, with respect to cost of packet forwarding. The cost of any given node is plotted along the X-axis. Graph 2 is similar to graph 1 except for the fact that here the condition for refinement of Nash equilibrium strategy is that of proportional fairness.



Graph 1. Cost vs Social Welfare at Social Welfare Maximizing Nash Equilibrium



Graph 2. Cost vs Proportional Fairness at Proportional Fairness Maximizing Nash Equilibrium

We also considered other network sizes with different cost values. The general trend of the graphs remains the same. As the cost increases, the social utility and proportional fairness decrease fast to zero. However, for moderate costs, the values of social utility and proportional fairness are non-zero. This means that cooperation is present when costs are not very high. Thus at the obtained Nash equilibria, multi-hop communication occurs successfully.

4 Conclusion

In this paper, we have a presented a game theoretic model to analyze and provide a solution to the Forwarders' Dilemma problem in wireless ad-hoc networks. We have restricted ourselves to a static network scenario because of the complexity of the problem.

We have shown that the proposed game possesses at least one Nash equilibrium. Indeed, there are multiple equilibria so that we select the ones that either maximize the social utility or the proportional fairness. It is shown that intermediate nodes do forward other nodes' packets at the equilibrium point, thus resulting in successful multi-hop communication. As the cost of forwarding increases, the social utility and proportional fairness decrease at the equilibrium point.

The presence of multiple Nash equilibria prevents us from predicting which one will actually exist in the system. In future we plan to explore how to design utility functions that would make the Nash equilibrium unique. Simulating the game in a larger network is also left as a future exercise.

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