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ANALYZING PACKET FORWARDING MECHANISM IN ADHOC NETWORKS USING GAME THEORY

KEYWORDS: Adhoc Network; Game Theory; Nash Equilibrium; Selfish nodes; Zero sum games.

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ABSTRACT *A wireless ad hoc network is characterized by a distributed, dynamic self organizing architecture. Each node in the network is capable of independently adapting its operation based on the current environment according to predetermined algorithms and protocols. Analytical models to evaluate the performance of ad hoc networks have been scarce due to the distributed and dynamic nature of such networks. Game theory offers a suite of tools that may be used effectively in modeling the interaction among independent nodes in an ad hoc network. In this paper, firstly we briefly introduce game theory; secondly we show that a strong mapping exists between traditional game theory components and the elements of an ad hoc network routing. In the final section of the paper we present a typical game theoretic model for analyzing selfishness in forwarding packets.*

I. INTRODUCTION

A wireless Adhoc network is a collection of mobile nodes communicating through wireless channels without any existing network infrastructure or centralized administration [1]. The application of mathematical analysis to the study of wireless Adhoc networks has met with limited success due to the complexity of mobility and traffic models, the dynamic topology, and the unpredictability of link quality that characterize such networks. The ability to model individual, independent decision makers whose actions potentially affect all other decision makers renders game theory particularly attractive to analyze Adhoc networks.

Game theory is the most interesting field of applied mathematics which involves the formal study of conflict and cooperation. Game theoretic concepts apply whenever the actions of several agents are interdependent. These agents may be individuals, groups, firms, or any combination of these. The concepts of game theory provide a language to formulate, structure, analyze, and understand strategic scenarios.

Game: A game consists of players, the possible actions of players, and consequences of the actions. The players are decision makers, who choose how they act. The actions of the players result in a consequence or outcome. The players try to ensure the best possible consequence according to their preferences. Each player evaluates the resulting outcome through a pay off or utility function representing his objectives [2]. The most fundamental assumption in game theory is rationality. Rational players are assumed to maximize their payoff.

The maximizing of one's payoff often referred to as selfishness. This is true in the sense that all the players try to gain the highest possible utility. In game theory, a solution of a game is a set of the possible outcomes. A game describes what actions the players can take and what the consequences of the actions are. The solution of a game is a description of outcomes that may emerge in the game if the players act rationally and intelligently. Generally, a solution is an outcome from which no player wants to deviate unilaterally. An outcome of a game is Pareto efficient, if there is no other outcome that would make all players better off. When a player makes a decision, he can use either a pure or a mixed strategy. If the actions of the player are deterministic, he is said to use a pure strategy. If probability distributions are defined the actions of the player, a mixed strategy is used. If mixed strategies are used, the players maximize their expected payoff.

II. CLASSIFICATION OF GAMES

Games can be classified into different categories according to their properties. The terminology used in game theory is inconsistent, thus different terms can. be used for the same concept in different sources.

Non cooperative and cooperative games

Cooperative games are also called coalition games. Non cooperative games, the actions of the single players are considered. Correspondingly, in coalition games the joint actions of groups are analyzed, i.e. what is the outcome if a group of players cooperate. Most game theoretic research has been conducted using non cooperative games, but there are also approaches using coalition games. Coalition games can be used to analyze heterogeneous ad hoc networks. If the network consists of nodes with various levels of selfishness, it may be beneficial to exclude too selfish nodes from the network if the remaining nodes get better quality of service that way.

Strategic and extensive games

In strategic or static games, the players make their decisions simultaneously at the beginning of the game. While the game may last long and there can be probabilistic events, the players cannot react to the events during the game. The prisoners dilemma and the battle of the sexes are both strategic games. Extensive game defines the possible orders of the events. The players can make decisions during the game and they can react to other. Extensive games can be finite or infinite of extensive games is repeated games, observe the outcome of the previous game before attend.

Zero-sum game

A game is called zero-sum game, if the sum of the utilities is constant in every outcome. What ever is gained by one player is lost by the other players[2]. Gambling is a typical zero-sum game.

III. NASH EQUILIBRIUM AND BEST RESPONSE

Formally, a normal form of a game G is given by G = (N, A, {ui}) where N = {1,2…,n} is the set of players (decision makers), Ai is the action set for player i, A = A1 x A2 ´ ….´ An is the Cartesian product of the sets of actions available to each player, and $\{u_i\}$ = { u1, u2…un} is the set of utility functions that each player i wishes to maximize, where ui : A □ R. For every player i, the utility function is a function of the action chosen by player i, ai, and the actions chosen by all the players in the game other than player i, denoted as a-i. Together ai and a-i, makeup the action tuple a. An action tuple is a unique choice of actions by each player. From this model,

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steady state conditions known as Nash equilibria can be identified. Before describing the Nash equilibrium we define the best response of a player as an action that maximizes her utility function f $\bar{\alpha}\,\bar{\alpha}$ given action tuple of the other players. Mathematically $\bar{\alpha}\,\bar{\alpha}$ is a best response by player ai to a-i , if

$$\bar{\alpha}\,\bar{\alpha}\ \hat{\imath}\{\text{argmax}\ u_i(a_i , \mathbf{a}_{-i}) \qquad (1)$$

A Nash equilibrium (NE) is an action tuple that corresponds to the mutual best response: for each player i, the action selected is a best response to the actions of all others. Equivalently, a NE is an action tuple where no individual player can benefit from unilateral deviation. Formally the action tuple $a^* = (a_1^*, a_2^*,\ldots, a_n^*)$ is a NE if

$u_i (a_i^*, \mathbf{a}_{-i}^*) \geq u_i (a_i , \mathbf{a}_{-i}^*)$ for □a_i□ A_i and for □i□ N. (2) a^*

The action tuples corresponding to the Nash equilibira are a consistent prediction of the outcome of the game, in the sense that if all players predict that a Nash equilibrium will occur then no player has any incentive to choose a different strategy.

To illustrate these basic concepts, consider a peer to peer file sharing network modeled as a normal form game. The players of the game are individual users who experience a tradeoff in sharing their files with others. For simplicity consider a network of three users. Each user has the operation of either sharing her files or not sharing. Thus the action set of each player is {Share, Not Share}. The payoff to each user is given by the sum of the benefits she experiences when other limited in resources. We assign the payoffs such that each user benefits by 1 unit for each other user that shares files and incurs a cost of 1.5 units in sharing her own files. The payoff matrix can be represented as in Table 1. In the payoff matrix, the payoff for user 1 is listed first, the payoff for user 2 is listed second, and the payoff for user 3 is listed third. Rather than attempting to represent the three dimensional action space as a single object, we have presented the action space in two two-dimensional slices.

Table 1. A Payoff Matrix for a three player peer-to-peer

User2 User1	Share	Not Share
Share	0.5,0.5,0.5	-0.5,2,-0.5
Not share	2,-0.5, -0.5	1,1,-1.5

User 3 = Share

User2 User1	Share	Not Share
Share	-0.5,-0.5,2	-1.5,1,1
Not share	1,-1,5,1	0,0,0

User 3 = Not share

From the payoffs we observe that the best response of each user irrespective of other users actions is to not share. The unique NE is the action tuple (Not share, not share, not share). Also it is evident that no user accrues any benefit by unilaterally deviating and sharing her files. One should not that the Nash equilibrium is not Pareto optimal in this case. The outcome (Share, share, share) would make all three players better off than the NE action tuple. Those familiar with game theory will recognize this formation as a three player version to the Prisoners' Dilemma game [3].

As seen from Table 1, selfish behavior may lead to a NE that is socially undesirable. Therefore from a system designer's perspective it is imperative to make the network robust to selfish behavior, perhaps by providing mechanisms that render selfish behavior unprofitable to the nodes that employ it. Game theory can be used to better understand the expected behavior of nodes and engineer ways to induce a socially desirable equilibrium.

1V. MODELING ADHOC ROUTING AS GAMES

In a game, players are independent decision makers whose payoffs depend on other players' actions. Nodes in an ad hoc network are characterized by the same feature. This similarity leads to a strong mapping between traditional game theory components and elements of an ad hoc network. Table 2 shows typical components of an ad hoc networking game.

Table 2. Typical mapping of Adhoc network components to a game.

Components of a game	Elements of an ad hoc network
Players	Nodes in the network
Strategy	Action related to the functionality being studied (e.g. the decision to forward packets or not, the setting of power levels, the selection of waveform/ modulation scheme)
Utility function	Performance metrics (e.g. throughput, delay, target, signal to noise ratio)

Game theory can be applied to the modeling of an ad hoc network at the physical layer (distributed power control and waveform adaptation), link layer (medium access control) and network layer (packet forwarding). Applications at the transport layer and above exist also, although less pervasive in the literature. A question of interest in all those cases is that of how to provide the appropriate incentives to discourage selfish behavior. Selfishness is generally detrimental to overall network performance; examples include a node's increasing its power without regard for interference it may cause on its neighbors (layer 1), a node's immediately retransmitting a frame in case of collisions without going through a back off phase (layer 2) or a node's refusing to forward packets for its neighbors (layer 3). In the next section, we outline game theoretic models for the network layer. Before that, however we discuss some of the benefits and common challenges in applying game theory to the study of ad hoc networks.

In this section we summarize potential applications of game theory to ad hoc networks, discussing issues at network layer in the protocol stack.

Network layer

Functionalities of the network layer include the establishment and updating of routes and the forwarding of packets along those routes. Issues such as the presence of selfish nodes in a network, convergence of different routing techniques as the network changes, and the effects of different node behavior on routing.

A recent application of game theory to ad hoc routing[4] focuses on the analysis of the effectiveness of three ad hoc routing techniques, namely link state routing, distance vector routing and multicast routing (reverse path forwarding), in the event of frequent route changes. The objective of the analysis is to compare and contrast the techniques in an ad hoc setting. These techniques are evaluated in terms of

- Soundness – whether routers have a correct view of the

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network to make the correct routing decisions under frequent network changes;

- Convergence – length of time taken by the routers to have a correct view of the network topology as nodes move; and
- Network overhead- amount of data exchanged among routers to achieve convergence.

Routing is modeled as a zero sum game between two players – the set of routers and the network itself. In a zero sum game [3] the utility function of one player (minimizing player) is the negative of the other's (maximizing player). The game has equilibrium when the minmax value of any players payoff is equal to its maxmin value. In a zero sum game, the maxmin value is defined as the maximum value that the maximizing player can get under the assumption that the minimizing player's objective is to minimize the payoff to the maximizing player. In other words, the maxmin value represents the maximum among the lowest possible payoffs that the maximizing player can get; this is also called the safe or secure payoff.

In the routing game the payoff to each player consists of two cost components, one being the amount of network overhead and the other varying with the performance metric under consideration. For example, for evaluating soundness the cost to the routers is 0 if all routers have a correct view of the topology when the game ends and 1 if any one router does not. The objective of the routers is to minimize the cost function. The action for the routers involved is to send routing control messages as dictated by the routing technique and update their routing information, and for the network to change the state of existing links from up to down and vice versa. The game is solved to determine the minmax value of the cost function. It serves to compare the different routing techniques in terms of the amount of routing control traffic required to achieve convergence and the soundness of the routing protocol to network changes. One of the main conclusions reached in the comparative analysis was that reverse path forwarding requires less control traffic to achieve convergence, against traditional link state routing. Another issue related to routing involves studying the effect of selfish nodes on the forwarding operation, as discussed next.

V.SELFISH BEHAVIOR IN FORWARDING PACKETS

The establishment of multi-hop routes in an ad hoc network relies on nodes' forwarding packets for one another. However, a selfish node, in order to conserve its limited energy resources, could decide not to participate in the forwarding process by switching off its interface. If all nodes decide to alter their behavior in this way, acting selfishly, this may lead to the collapse of the network. The works of [5][6][7][8] develop game theoretic models for analyzing selfishness in forwarding packets. Under general energy-constraint assumptions, the equilibrium solution for the single-stage game results in none of the nodes' cooperating to forward packets[9]. A typical game theoretic model that leads to such an equilibrium is parameterized in Table 4. Now, consider strategy $\bar{s}$ = {$\bar{s}$1 , $\bar{s}$2 , $\bar{s}$3 , $\bar{s}$n} and let σ = {k Î N | $\bar{s}$k =1}. The utility of any node k Î σ is given by

$$u_k(\bar{s}) = (|\sigma| - 1) - s_k = |\sigma| - 2$$

Let us consider that node k unilaterally deviates to a strategy of not participating. The utility of node k is given by uk (s' k , $\bar{s}$-k) = |σ| −1 . Since uk (s'k , $\bar{s}$-k) > uk ($\bar{s}$) , strategy $\bar{s}$ can only be a Nash equilibrium when σ = f.

Table 4. A game theoretic model leading to equilibrium

Symbol	Meaning
N	The set of nodes in the adhoc network; {1,2,…n}.
S_k	Action set for node k; Sk={0,1}
s_k	Action node k; s_k = 0 (not participate) and s_k = 1 (participate)
S	Joint action set; S = ´ kÎN Sk
s	s = { s1, s1 , …., sn}; s Î S
ακ(s)	Benefit accrued when other nodes participate; e.g $\left(\alpha_k(\mathbf{s}) = \sum_{i=1, i\neq k}^{n} s_k\right)$
βκ(s)	Benefit (or cost) to node k when it participates; for energy constrained nodes it is negative. e.g. : bk(s)= -sk
υκ(S)	Utility of the node uk(s) = ak(s)+ bk(s)

However, in practical scenarios adhoc networks involve multiple interactions among nodes/players with a need for nodes to participate. In order to account for such interactions, the basic game is extended to a repeated game model. Different repeated game mechanisms such as tit-for-tat [10] is investigated to determine conditions for a desirable NE – one in which all nodes would forward packets for one another leading to a high network-wide social welfare. The tit-for-tat based mechanisms provide an intrinsic incentive scheme where a node is served by its peers based on its past behavioral history. As a result a node tends to behave in a socially beneficial manner in order to receive any benefit in the later stages.

VI. CONCLUSION

In this paper, we introduced the basic concepts of game theory. Game theory can be used to analyze the existing systems or it can be used as a tool to design new systems. Existing systems can be modeled as games. The models can be used to study the properties of the system. In the second half of the paper, we show that there is a strong mapping existing between traditional game theory and the elements of an Adhoc routing. In the final section of the paper, we have presented a typical game theoretic model for analyzing selfishness in forwarding packets.

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