Seminar Work

"Using Game Theory to Analyze Wireless Ad Hoc Networks."

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1 Introduction

Nowadays wireless communications are a very important part of people's life. A significant role in their development is played by so called ad hoc networks. They inherit the traditional problems of wireless and mobile communications, such as bandwidth optimization, power control, and transmission quality enhancement. A powerful tool for the analysis of such networks is game theory. Here we discuss the applicability of game theory to the power control and waveform adaptation, media access control, routing and node participation.

2 Wireless Ad Hoc Networks

In Latin, ad hoc literally means "for this", further meaning "for this purpose only". Wireless ad hoc networks have a distributed, dynamic, self-organizing architecture. That means that wireless hosts can communicate with each other over wireless links without central control and in the absence of a fixed infrastructure. Each node is willing to forward data for other nodes and so the determination of which nodes are willing to do it at a particular moment is made dynamically based on the network connectivity. The scientific term for such behavior is multihop nature - every host is also a router [1]. In order to analyze this complicated system, a flexible tool is needed. So we try to map traditional game theory components and elements of an ad hoc network and so to model the interaction among independent nodes in such a network.

3 Basics of Game Theory

There are two main branches of game theory: cooperative and non-cooperative game theory. Non-cooperative game theory deals with intelligent individuals who interact with one another in an effort to achieve their own goals. Here we consider the non-cooperative game theory models. They have a wide range of applications – form politics, economy and business through biology, philosophy, computer science and logic. This paper focuses on the use of game theory in the computer science world and particularly, in the analysis of wireless ad hoc networks. Game theory is a branch of applied mathematics. Its goal is to analyze complex interactions between rational decision makers, also called players, and to predict the outcome of those interactions. Each player has particular interests or preferences called utilities. A decision maker is supposed to follow a strategy and, in the simplest case, each player picks up a single action from a set of possible actions. After all players have selected their actions one can see the resulting outcome. The influence of each rational decision maker over the resulting outcome expresses the interaction between players. The normal form representation of a game G is given by $G = \langle N, A, \{u_i\} \rangle$ where $N = \{1, 2, \ldots, n\}$ is the set of players, A_i is the action set for player i, $A = A_1 \times A_2 \times ... \times A_n$ is the Cartesian product of the sets of actions available for each player, and $u_i = \{u_1, \ldots, u_n\}$ is the set of utility functions that each player wants to maximize, where $u_i : A \rightarrow \Re$. The utility function for every player i is valid for the action chosen by player i, denoted as a_i, and for a_{-_i} – the actions selected by all other players different from i. All together it is denoted as an action tuple **a** and means this particular sequence of action choices. With this notation different situations can be modeled and steady-state conditions known as Nash Equilibria can be identified. The definition of the term Nash Equilibria is easier to understand introducing another important term – best response by a player i to a_{-i}. That is the strategy (or strategies) which produces the most favorable immediate outcome for the current player, taking other players' strategies as given. Now it will be easier to explain the term Nash Equilibrium (NE), which is named after John Nash who proposed it. That is a set of strategies, one for each player, such that no player has incentive to unilaterally change his action. Players are in equilibrium if a change in strategies by any one of them would lead that player to earn less than if he remained with his current strategy – this definition corresponds to mutual best response. For games in which players randomize, the expected or average payoff must be at least as large as that obtainable by any other strategy. Mathematically, the action tuple $a^* = (a_1^*, a_2^*, a_3^*, ..., a_n^*)$ is a NE if $u_i(a_i^*, a_{-i}{}^*) \geq u_i(a_i^*, a_{-i}{}^*)$ for $\forall a_i \in A_i$

and for $\forall i \in N$. If all rational decision makers foresee the occurrence of NE then no player has any incentive to look for another strategy. In this sense Nash Equilibria are a tool for consistent prediction of the outcome of a game. But if efficiency is desired, then the situation is not the same – the existence of Nash Equilibrium does not guarantee that the outcome of a game will be favorable for all players. Another method is used when efficiency is important – Pareto Optimality, named after the Italian economist Vilfredo Pareto. A result of a game is Pareto optimal if there is not another outcome that makes a player better off without sacrificing the well-being of at least one other rational decision maker of that game. Mathematically, Pareto optimality can be expressed in such a way: an action tuple $a = (a_1, a_2, a_3, ..., a_n)$ is Pareto-optimal if and only if there exists no other action tuple $b = (b_1, b_2, b_3, ..., b_n)$ such that $u_i(b) \geq u_i(a)$ for $\forall i \in N$, and for some $k \in N$, $u_k(b) > u_k(a)$.

User 3 = Share		
User 2 \ User 1	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 = Not share		
User 2 \ User 1	Share	Not share
Share	-0.5, -0.5, 2	-1.5, 1, 1
Not share	1, -1.5, 1	0, 0, 0

These basic concepts are easier to be understood through an example – a peer-to-peer file sharing network with only three users is considered and it is modeled through the above introduced notation for the normal form of a game. The possible actions for each player are either sharing his files or not sharing - A_i = Share, Not share. The payoff is equal to the sum of all benefits the player gets when other users share their files minus the costs the player gains when he shares his own files. For simplicity and easy calculation we assign values – benefits = 1 unit and cost = 1.5 units. The results are represented in the payoff matrix in Table 1, where the first entry of the result vector expresses the value of User 1's payoff, the second entry the payoff of User 2 and the third entry User 3's payoff. From the results one can see that the best response of a player is when he does not share and only uses the resources that are shared by the other users. According to the definition the unique NE will be created through the mutual best response of all users. In our example that means that no user gains any benefit and the result from the action tuple $A = (Notshare, Notshare, Notshare)$ is $(0, 0, 0)$. The payoff matrix makes it obvious that a player would decrease his payoff by unilaterally deviating from the strategy "Not share". The case where at least one user is better off after the selected action and no one's payoff is reduced – which corresponds to the definition of Pareto optimality – is the action tuple $A = (Share, Share, Share)$. Then all users will be better off $l(0.5, 0.5, 0.5)$. The idea of this example is to describe the meaning of the two terms and to show that a Nash equilibrium is *not* Pareto optimal in this case.

4 Why game theory?

At first game theory has been applied as an analyzing tool to wired networks. But due to the rapid development of wireless technologies it was needed to further study and analyze their performance. As a result of the studies game theoretic models developed for ad hoc networks that focus on distributed systems came into existence. In order to understand the actual problems that have to be solved by a designer of a distributed system we consider an ad hoc network implementing a pure slotted Aloha protocol. Aloha refers to a simple communications scheme in which each source in a network sends data whenever there is a data packet to be sent. If it successfully reaches the destination, the next data packet is sent. If it fails to be received at the destination, it is resent. Slotted Aloha protocol means that the system is synchronous and the time is divided into slots. In this way packets overlap completely or not at all. Of course, the cases where packets overlap completely are not rare at all and these cases are called collisions. Collision avoidance is one of the main problems. Therefore an algorithm is needed which has to be capable of setting the optimal retransmit probability dynamically. But would such an algorithm have a desirable steady-state? And if it does, would the network behavior converge to this steady-state? Another important issue is the number of users. They are going online and offline all the time, so their number is dynamical too. What happens if the users' number grows too much at some point? Would that have any negative effects on the network? An interesting question is also how selfish behavior of individual nodes influences the performance of the system. These are the type of questions game theory has been utilized to answer, not just with respect to Media Access Control (MAC) protocols, but also distributed adaptations at the physical, network, and transport layers. The main benefits of applying game theory to ad hoc networks are: analysis of distributed systems, cross layer optimization and design of incentive schemes through which selfish behavior of users would be avoided.

5 Modeling Ad Hoc Networks as Games

Game theory studies decision making in conflict situations. Such a situation exists when two or more decision makers who have different objectives act on the same system or share the same resources. That sounds like a very simple description of nodes in a network. That's why game theory is so applicable to ad hoc networks - it's easy to model an ad hoc network through the traditional game theory components. A typical mapping of ad hoc network components to a game is shown in Table 2.

Game components	**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)

TABLE 2. Typical mapping of ad hoc network components to a game.

The primary architectural model for inter-computing and internetworking communications is considered to be the OSI 7 layers reference model for network communication. Game theory can be applied to the modeling of an ad hoc network at most of the layers, but the prevailing part of the technical literature is focused on the analysis of the first three layers: physical, data link and network layers. The analysis of these three layers will be the main contribution of this paper too.

6 Game Theory in Ad Hoc Networks: A Layered Perspective

6.1 Physical Layer

The physical layer is the lowest of seven hierarchical layers. It performs services requested by the Data Link Layer and is responsible for bit-level transmission between network nodes. This layer defines items such as: connector types, cable types, voltages, and pin-outs. From physical layer perspective, performance is generally a function of the effective signal-to-interference-plus-noise ratio, shortly SINR, at the node(s) of interest. That is the ratio of the received strength of the desired signal to the received strength of undesired signals - noise and interference. So when the perceived SINR changes, the nodes in a network react to these changes by adapting their signal and in this way physical layer interactive decision making process occurs. The signal adaptation can take place in the transmit power control and the signaling waveform – modulation, frequency, bandwidth. In order to model these physical layer adaptations using game theory, the notation in Table 3 is introduced.

Symbol	**Meaning**	**Symbol**	**Meaning**
N	The set of decision making nodes in the network; 1, 2,. . . , n.	**P**	The power space formed from the Cartesian product of all P_j. $P = P_1 \times P_2 \times \ldots \times P_n$
h_{ij}	The link gain from i to j. Note this may be a function of the waveform selected.	**p**	A power profile (vector) from P formed as $p = (p_1, p_2, \ldots, p_2)$.
H	The network link gain matrix. $\text{H} = \begin{bmatrix} 1 & h_{12} & h_{13} & \cdots & h_{12} \\ h_{21} & 1 & & & \vdots \\ h_{31} & & \ddots & & \\ \vdots & & & \ddots & \\ h_{n1} & h_{n2} & \cdots & \cdots & 1 \end{bmatrix}$	Ω_j	The set of waveforms known by node j.
		ω_j	A waveform chosen by j from Ω_j.
		Ω	The waveform space formed from the Cartesian product of all $\Omega_j.\Omega = \times_{j \in \text{N}} \Omega_j$.
P_j	The set of power levels available to node j. This is presumed to be a subset of the real number line.	ω	A waveform profile (vector) from Ω formed as $\omega = (\omega_1, \omega_2, \ldots, \omega_n)$.
p_j	A power level chosen by j from P_j.	$u_j(p, \omega, H)$	The utility derived by j.

TABLE 3. Game theoretic model for physical layer adaptations in ad hoc network.

On the basis of the above presented notation a general physical layer adaptation game can be modeled as: $G = \langle \text{N}, \{P_j \times \Omega_j\}, \{p, \omega, H\} \rangle$, where each node selects a power level, p_j, and a waveform, ω_j, according to the current situation which is influenced by the action choices of the other nodes.

6.1.1 Power Control

Mobile computing relies on low-power communication. Since devices are often idle, many researchers have investigated mechanisms to reduce idle power. Now we will take a closer look at one of the many algorithms for distributed power control in 802.11 networks. The goal here is to minimize the energy cost of communication between any given pair of neighboring nodes if such communication is possible. The nodes can choose from up to ten different power levels. When a node has to transmit an addressed message, it uses a signaling protocol RTS-CTS-DATA-ACK (see Figure 1). RTS-CTS-DATA-ACK means Request to Send – Clear to Send – Data – Acknowledge. In this protocol the message header formats for CTS and DATA messages are altered so they include a value which is the ratio of the received signal strength of the last received message to the minimum acceptable signal strength at the node currently transmitting the message. When a receiver receives an RTS message, it will reply to the transmitter with a CTS message. In the header part of this reply message the ratio of the received signal strength of the RTS message to the minimum signal strength that is acceptable by this receiver will be encoded. Similarly, when transmitting the DATA message, the transmitter will encode into it the ratio with respect to the received CTS. Thus, during one RTS-CTS-DATA-ACK exchange, both the transmitter and the receiver inform each other about the quality of their transmitted signals. Both nodes now have the opportunity to alter their transmit power levels for further communication between each other[2, 3].

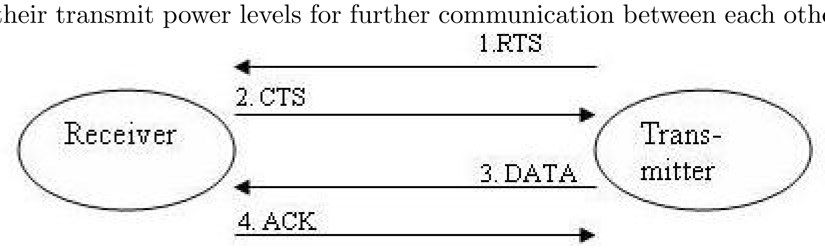

FIGURE 1. IEEE 802.11 Signaling for Addressed Messages

This power control algorithm can be modeled as a normal form game with the notation introduced in Table 3. We assume that each node, i, in the set of nodes, N, is maintaining a single link to its node of interest, v_i. As each node is attempting to maintain a target SINR, an appropriate utility function for it is given by:

$$u_i(\mathbf{p}) = -\left[\hat{y}_i - \frac{h_{iv_i} p_i}{\sigma_{v_i} + \sum_{j \in N, j \neq i} h_{jv_i} p_j}\right]^2$$

where σ_{v_i} is the noise at v_i and $\hat{y}_i$ is the target SINR of player i. A game model for this algorithm is thus given by $G = \langle N, P, \{u_i\} \rangle$.

6.1.2 Waveform Adaptation

Because of the distributed, dynamic, self-organizing architecture of wireless ad hoc networks nodes have to independently adapt in a way such that the interference in the network is minimized. Thus special distributed waveform adaptation strategies which reduce interference are required. Greedy interference avoidance algorithms by waveform adaptation (wherein users choose waveforms that increase their own SINR or utility) for networks with a centralized receiver have been extensively investigated. These algorithms are shown to converge to a set of waveforms which maximize the sum capacity of the multiple access channel. However, in wireless systems where users talk to multiple uncoordinated receivers as in an ad hoc network, direct applications of the same techniques might not lead to a stable NE. This is caused by the asymmetry of the mutual interference between users at different receivers, leading the users to adapt their sequences in conflicting ways [4]. That is why greedy interference schemes cannot be directly extended to ad hoc networks. A framework based on potential game theory such as the one described here can be used to construct convergent waveform adaptation games in such a scenario. A potential game possesses one global potential function through which the incentive of all players to change their strategy can be expressed. The potential function is a useful tool to analyze equilibrium properties of games, because the incentives of all players are mapped into one function, and the set of pure Nash equilibria can be found by

simply locating the local optima of the potential function. Games can be either ordinal or cardinal potential games. An ordinal potential game is a normal form game whose objective functions are structured such that there exists some function $P : A \rightarrow \Re$ which satisfies the following property for all players:
$P(a_i, a_{-i}) > P(b_i, a_{-i}) \Leftrightarrow u_i(a_i, a_{-i}) > u_i(b_i, a_{-i}) \forall a_i, b_i \in A_i, \forall a_{-i} \in A_{-i}$
In other words it must be possible to construct a single-dimensional function where the sign of the change in value is the same as the sign of the change in value of the deviating player.

6.2 Media Access Layer

The Media Access Control Layer is one of two sublayers that make up the Data Link Layer of the OSI [7] model. The MAC layer is responsible for moving data packets to and from one network interface card to another across a shared channel. It controls how a computer on the network gains access to the data and permission to transmit it – usually through carrier sense multiple access with collision detection (CSMA/CD) network control protocol [5]. Because of the many users contending for access to a shared communications medium, the so called medium access control problem occurs. This problem could be effectively analyzed through the means of game theory. In these medium access control games, selfish users try to increase their utility by obtaining an unfair share of access to the channel. As a result of these actions the ability of other users to access the channel is decreased. MacKenzie and Wicker pose the slotted Aloha protocol as such a game. In a given time-slot the action set Ai for each user is $A_i = \{Transmit, Wait\}$. If node i is the one and only which transmits in a given time-slot, then that user's transmission is successful. If more than one user wants to transmit in the same time-slot, then all of their transmissions are unsuccessful. Let's suppose that the payoff associated with a successful transmission is 1, while the cost of transmission is c, where $0 < c < 1$. A user who waits will receive a payoff of 0; a user who transmits will receive a payoff of either $1{-}c$ - if the transmission is successful - or $-c$ - if the transmission is unsuccessful. It is also assumed that each user has a discount factor $0 < d < 1$ that is used to discount future payoffs. So, the present value of waiting for 10 slots and then transmitting with certain success is $(1{-}c)\delta^{10}$. The goal of a user is to maximize the expected discounted value of his payoff. It can be mathematically proved that for the right value of c, the throughput of a slotted Aloha system [6] with selfish users is exactly the same as the throughput of a system in which the users work together to maximize system throughput. This statement suggests that for the design of an efficient random access protocol the assumption that nodes have to be cooperative is not of such great importance.

6.3 Network Layer

This layer provides switching and routing technologies, creating logical paths for transmitting data from node to node. Routing and forwarding are functions of this layer, as well as addressing, internetworking, error handling, congestion control and packet sequencing. Game theory can be used here to analyze the convergence of different routing techniques as the network changes, presence of selfish nodes in a network, and the effects of different node behavior on routing.

6.3.1 Traditional Routing Techniques

Three main ad hoc routing techniques will be compared and contrasted in this paper. Important issues for the evaluation of the different protocols are: soundness, convergence and network overhead. The first term means if the routers have a correct view over the frequently changing network so the correct routing decision can be made. Convergence is the time that the routers need to get the correct overview. Network overhead is the amount of data exchanged among routers to achieve convergence. The first very important routing technique is link state routing. The main feature of this protocol is that every node possesses a copy of the network topology map that shows which nodes are connected to which other nodes. So the calculation of the next best hop is made locally by each node without any exchange of information with the others. The collection of best next hops forms the routing table for the node. That is the main difference with the second important routing technique, namely the distance vector routing protocol. This protocol is characterized by the fact each node shares its routing table with its neighbors. That means that the router has to inform its neighbors of topology changes periodically and, in some cases, when a change is detected in the topology of a network. The third routing technique, which will be described here, is the reverse path forwarding. This is a technique used in modern routers for the purposes of ensuring loop-free forwarding of multicast packets in multicast routing and to help prevent IP address spoofing in unicast routing.

The intuition behind modeling routing as a game is to note that the problem of routing can be understood as a contest between the network and the routers. The routers are competing with the network that is trying to outwit them. So a routing protocol can be modeled as a zero sum game between the network and the routers. Zero-sum describes a situation in which a participant's gain or loss is exactly balanced by the losses or gains of the other participant(s). The game has equilibrium when the minmax value of any player's payoff is equal to its maxmin value. Minmax is a method through which the nodes try to minimize the maximum possible loss and maxmin is an alternative – the network tries to maximize the minimum gain. The payoff consists of two components. The first is the network overhead and the second is a cumulative component that contains all other all other metrics that are being considered. For example, we will evaluate soundness[8]. If all routers have a correct view of the topology when the game ends, the cost to the routers is 0 and respectively 1 if any one router does not. The objective of the routers is to minimize the cost function – so as much as possible routers have a correct overview. The action for the routers involved is to send routing control messages and update their routing information, and for the network to set the state of existing links from up to down and vice versa. 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.

6.3.2 Selfish behavior in forwarding packets

Wireless ad hoc networks have multihop nature. That means that every node is also a router and its duty is to forward packets for the other nodes. But there are nodes which behave selfishly and don't participate in the routing process. If the majority of the users acts in such a way that could lead to a suboptimal equilibrium where nodes, through their actions, reach an undesirable steady state from a network perspective. In order to describe such interaction between nodes the basic game is extended to a repeated game model. An example for repeated game mechanisms is the *tit-for-tat* strategy. A node using it will cooperate initially and then will choose the same action as the last one of his opponent. If the opponent previously was cooperative, the agent is cooperative. If not, the agent is not. As a result of this strategy a node tends to behave in a socially beneficial manner in order to receive any benefit in the later stages. The idea of the tit-for-tat strategy has been extended to the so called *grim trigger* mechanism. It is used in games where nodes are asked to provide resources for others voluntarily [9]. A node using this strategy will cooperate initially and then if the opponent defects, the node will not cooperate till the end.

6.3.3 Incentive mechanisms

In view of avoiding selfish behavior of nodes incentive mechanisms are introduced. The latter fall into two categories: credit-exchange-based systems and reputation-based mechanisms. Basic characteristic of the first category is that a node is credited for cooperating with the other nodes and debited when requesting services from them. Also a "virtual currency" is introduced in order to implement the charge and reward scheme. A credit exchange system requires a tamper-proof hardware module to prevent nodes from cheating during "token" exchange.

As it was stated at the beginning of the present subchapter there exist reputation based mechanisms. Basic characteristic of these mechanisms is that the nodes have reputation values. These are given by each node to its neighbors on the basis of its direct interactions with them and on indirect reputation information obtained from other nodes. Further, this reputation mechanism is modeled as a complex node strategy in a repeated game model. The analysis of the game helps to assess the robustness of the reputation scheme against different node strategies and derive conditions for cooperation.

7 Concluding Remarks

Emerging research in game theory applied to ad hoc networks shows much promise to help understand the complex interactions between nodes in this highly dynamic and distributed environment. The focus has been on maximizing throughput using random access techniques for the wireless medium, and on developing robust techniques to deal with selfish behavior of nodes in forwarding packets. Other areas to which game theory has been applied include distributed power control and interference avoidance.

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