Game Theory Models for IEEE 802.11 DCF in Wireless Ad Hoc Networks

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Abstract

Because wireless nodes decide their channel accesses independently in the IEEE 802.11-based ad hoc networks, and the channel access of a node has an influence on those of its neighboring nodes, game theory naturally becomes a useful and powerful tool to research this kind of network. In this article a game model is proposed to interpret the IEEE 802.11 distributed coordination function mechanism. In addition, by designing a simple Nash equilibrium backoff strategy, we present a fairness game model. Our simulation results show that the new backoff strategy can improve TCP performance almost perfectly.

Introduction

Wireless ad hoc networks consist of a collection of peer wireless mobile or stationary nodes that are capable of communicating with each other without any help from fixed infrastructures. The interconnections among nodes often change continually and arbitrarily. Nodes within each other's radio range (one-hop) communicate directly via wireless links, while those that are far apart use other nodes as relays in multihop routing. These networks will play an increasingly important role in many environments, such as ad hoc networking for collaborative and distributed computing, disaster recovery, crowd control, and search-and-rescue.

Currently, the IEEE 802.11 distributed coordination function (DCF) [1] has been the de facto access standard, widely used in almost all of the testbeds and simulations for wireless ad hoc network research. It provides two access schemes, the basic scheme and the request to send/clear to send (RTS/CTS) scheme. In the basic scheme, a pair of source and destination nodes only exchang data frames and acknowledgment (ACK) frames, while the RTS/CTS scheme adds an RTS/CTS dialog preceding the data frame to reduce the probability of collisions on the channel since the collision probability of an RTS frame (20 octets) is less than that of a data frame (up to 2346 octets). In the RTS/CTS scheme, when a node wants to transmit a data frame, it first transmits an RTS frame to reserve the channel. The destination replies with a CTS frame if it is ready to receive. If the source receives the CTS frame successfully, it starts to transmit the data frame; then the destination replies with an ACK frame to the source after receiving the data frame. If the source does not receive the CTS frame successfully, it times out waiting for the CTS frame and adopts the binary exponential backoff (BEB) algorithm to compute a new random backoff time with a higher range to retransmit the RTS frame with lower collision probability.

At each RTS retransmission, the backoff time is uniformly chosen in the range (0, $CW - 1$), where CW is the size of the contention window depending on the number of failed transmissions for the RTS frame. At the first retransmission attempt, CW is equal to the minimum contention window CW_{min}. After each unsuccessful transmission, CW is doubled up to the maximum value CW_{max} above which CW remains the same. The RTS frame is dropped after seven failures.

Obviously, according to the IEEE 802.11 DCF, there are no central nodes (e.g., base stations or access points) in ad hoc networks to control nodes' channel access, and all nodes transmit their data frames competitively. The channel access of each node has a direct influence on those of its neighboring nodes. The interactions give us an intuition that game theory would be a very good tool to model and analyze the IEEE 802.11 DCF. In addition, the BEB algorithm causes the fairness problem among TCP flows in multihop ad hoc networks because it always favors the latest successful nodes. Game theory is also a powerful tool to resolve this unfairness problem. In this article we begin with a brief introduction to game theory and then propose a simple game model to interpret the IEEE 802.11 DCF mechanism. Finally, by designing a simple Nash equilibrium backoff strategy, we present a fairness game model that can greatly improve the fairness of TCP flows in the multihop ad hoc networks.

Game Theory

Game theory, defined in the broadest sense, is a collection of mathematical models formulated to study situations of conflict and cooperation. It is concerned with finding the best actions for individual decision makers in these situations and recognizing stable outcomes. The object of study in game theory is the game, defined to be any situation in which:

- There are at least two *players*. A player may be an individual, a company, a nation, a wireless node, or even a biological species.
- Each player has a number of possible *strategies*, courses of action he or she may choose to follow.
- The strategies chosen by each player determine the *outcome* of the game.
- Associated with each possible outcome of the game is a collection of numerical *payoffs*, one to each player. These payoffs represent the value of the outcome to the different players.

The pioneering analysis of game theory was the study of a duopoly by Cournot in 1838; however, game theory was not established as a field in its own right until the monumental *Theory of Games and Economic Behavior* by von Neumann and Oskar Morgenstern in 1944. In 1950 John Nash demonstrated that finite games always have a Nash equilibrium (also called a strategic equilibrium). A Nash equilibrium is a list of strategies, one for each player, which has the property that no player can unilaterally change his/her strategy and get a better payoff. This is the central concept of noncooperative game theory and has been a focal point of analysis since then. Game theory received special attention in 1994 with the awarding of the Nobel prize in economics to John Nash, John Harsanyi, and Reinhard Selten.

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	Static game	Dynamic game
Complete information game	Complete information static game Nash equilibrium John Nash (1950, 1951)	Complete information dynamic game Subgame perfect Nash equilibrium Reinhard Selten (1965)
Incomplete information game	Incomplete information static game Bayesian Nash equilibrium John Harsanyi (1967–1968)	Incomplete information dynamic game Perfect Bayesian Nash equilibrium Reinhard Selten (1975)

TABLE 1. *Categories of noncooperative games, corresponding equilibria, and the main research areas of the three winners of the 1995 Nobel prize in economics.*

Games may generally be categorized as noncooperative and cooperative games.

Noncooperative Game Theory

Noncooperative game theory is concerned with the analysis of strategic choices and explicitly models the process of players' making choices out of their own interests. Noncooperative games can be classified into a few categories according to several criteria. According to whether the players' moves are simultaneous or not, noncooperative games can be divided into two categories: static and dynamic games. In a static game, players make their choices of strategies simultaneously, without knowledge of what the other players are choosing.[1] Static games are most often represented diagrammatically using a *game table* that is called the *normal form* or *strategic form* of the game. In the dynamic game players involve strategic situations in which there is a strict order of play. Players take turns to make their moves, and they know what players who have gone before them have done. Dynamic games are most easily illustrated using *game trees*, which are generally referred to as the *extensive form* of a game. The trees illustrate all of the possible actions that can be taken by all of the players and also indicate all of the possible outcomes from the game. According to whether the players have full information of all payoff-relevant characteristics about the opponents or not, the noncooperative game can be classified into two types: complete information and incomplete information games. In the former each player has all the knowledge about others' characteristics, strategy spaces, payoff functions, and so on, but this is not so for the latter.

Table 1 shows four kinds of noncooperative games, corresponding equilibrium concepts, and the main research areas of the three Nobel prize winners.

Cooperative Game Theory

A cooperative game (also called *coalitional*) is a game in which the players can make binding commitments, as is not the case in the noncooperative game. Analysis in cooperative game theory is centered around coalition formation and distribution of wealth gained through cooperation. Within these two areas, finding procedures leading to outcomes that are most likely to occur under reasonable rationality assumptions in various game situations, and devising solution concepts showing attractive stability features are primary concerns in most research endeavors. Cooperative game theory is most naturally applied to situations arising in political science or international relations, where concepts like power are most important.

The definition draws the usual distinction between the two theories of games, but the real difference lies in the modeling approach. While in noncooperative game theory the notion of the Nash equilibrium is pervasive in capturing most aspects of stability, in cooperative game theory there is no solution concept dominating the field in such a way. Instead, there is a multiplicity of solutions, which is not due to the weakness of the theory, but rather to the inherent diversity of conflict situations into which it attempts to provide insight. Moreover, the main focus of the noncooperative game is individual rationality and individual optimal strategy, but the cooperative game emphasizes collective rationality, fairness, effectiveness, etc., which mean different things to different people. The reader who would like to learn more about game theory should consider *Straffin's Game Theory and Strategy* [2] and Dutta's *Strategies and Games* [3] as the starting points.

[1] *A game is also simultaneous when players choose their actions in isolation, with no information about what other players have done or will do, even if the choices are made at different points in time.*

		Klein: Confess	Klein: Not confess
Calvin	Confess	(5,5)	(0,15)
	Not confess	(15,0)	(1,1)

FIGURE 1. *The Prisoners' Dilemma.*

An Example: The Prisoners' Dilemma

To make readers understand the important concepts mentioned above, we illustrate them with a famous game paradigm, the Prisoners' Dilemma, which was first analyzed in 1950 at the RAND Corporation by Melvin Dresher and Al Tucker. The story underlying the game goes as follows [3]. Two prisoners, Calvin and Klein, are arrested for a suspected crime and interrogated in separate rooms. The clever district attorney talks to each prisoner separately, and tells them that she more or less has the evidence to convict them but they could make her a little easier and help themselves if they confess to the crime. She offers each of them the following deal: "Confess to the crime, turn a witness for the State, and implicate the other guy, you will do no time. Of course, your confession will be worth a lot less if the other guy confesses as well. In that case, you both go in for five years. If you do not confess, however, be aware that we will nail you with the other guy's confession, and then you will do 15 years. In the event that I cannot get a confession from either of you, I have enough evidence to put you both away for a year."

Obviously, the Prisoners' Dilemma is a complete information static noncooperative game between two players (Calvin and Klein). Each player has two pure strategies: *Confess* or *Not confess*. Figure 1 shows the strategy form (payoff matrix) of this game. Calvin chooses a row, and simultaneously Klein chooses one of the columns. The strategy combination (*Con-*

		Node 2	
		Not transmit	Transmit
Node 1	Not transmit	(u_i, u_i)	(u_i, u_s)
	Transmit	(u_s, u_i)	(u_f, u_f)

FIGURE 2. *The DCF game with two nodes.*

fess, *Confess*) has payoff *S* for each player; and the combination (*Not confess*, *Not confess*) gives each player payoff 1. The combination (*Confess*, *Not confess*) results in payoff 0 for Calvin and 15 for Klein, and when (*Not confess*, *Confess*) is played, Calvin gets 15 and Klein gets 0. A fundamental assumption of game theory is that each player is individually rational; in other words, he always chooses a strategy that gives the payoff he most prefers, given what he expects his opponents to do. Another assumption is that the rationality of all players is common knowledge;[2] thus, each player knows other players are also rational. Note that from each player's point of view, a smaller payoff is preferred to a bigger one since the payoff is the number of years a player is imprisoned. Therefore, *Confess* is the best strategy for each rational player whichever strategy is chosen by his partner (in fact, each player is convinced that his partner will choose *Confess*). The strategy profile (*Confess*, *Confess*) is composed of the best strategy that each player chooses and thus is a Nash equilibrium of the game. At last each player (prisoner) will be imprisoned for five years; this result is just what the district attorney expected.

An interesting fact in the Prisoners' Dilemma is that from the pair's point of view, the result of the Nash equilibrium (*Confess*, *Confess*) is obviously inferior to the result of the strategy profile (*Not confess*, *Not confess*), which is (1, 1). Therefore, the Nash equilibrium of this game is not Pareto optimal. An outcome is said to be Pareto optimal if it is impossible to better the payoff of any player without destroying the payoff of other players. Note that the word "optimal" here does not mean "best," just "not obviously inferior to some other outcome." The Prisoners' Dilemma has three Pareto optimal outcomes: (*Confess*, *Not confess*), (*Not confess*, *Confess*) and (*Not confess*, *Not confess*). This fact reveals that individual rationality is often incompatible with collective rationality (the players form a coalition and cooperatively choose a strategy to ensure the coalition the best payoff) in noncooperative games.

Another interesting fact is that if the game is played not just once, but repeated infinitely, the two players might cooperatively choose the strategy Not confess in early plays in hope of arriving at the mutually beneficial outcome (*Not confess*, *Not confess*) rather than the unprofitable result (*Confess*, *Confess*). One Nash equilibrium strategy profile of the infinitely repeated game to ensure cooperation is called grim strategy: each player always chooses the cooperative strategy *Not confess* in each subgame (a Prisoners' Dilemma game) until his partner chooses the strategy *Confess*, and then he always chooses the strategy *Confess* in the following games to punish the betrayer. Therefore, a coalition and cooperation form in the infinitely repeated game because each player is afraid of the punishment by his partner; thus, individual rationality becomes consistent with collective rationality.

[2] *A fact is common knowledge if all players know it, and know that they all know it, and so on.*

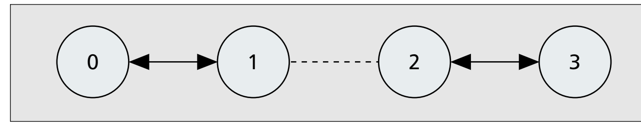

FIGURE 3. *Two TCP sessions. The first session is between 0 and 1, and the second between 2 and 3.*

Application of Game Theory

From the Prisoners' Dilemma, we can find that as the study of how players should rationally play games, game theory has the following salient characteristics:

- Each player would like the game to end in an outcome that gives him/her as good a payoff as possible.
- Each player has some control over the outcome, since his/her choice of strategy will influence it.
- The outcome is not determined by one player's choice alone, but also depends on the choice of all the other players; this is where conflict and cooperation enter. There may be conflict because different players will, in general, value outcomes differently. There is a chance for cooperation because several players together may be able to coordinate their strategies to obtain an outcome with better payoffs for all of them.

Therefore, game theory is a powerful tool in many areas, such as war, politics, economics, sociology, psychology, biology, communications, networking, and so on, where conflict and cooperation exist. The application areas of game theory in communications and networking include flow and congestion control, network routing, load balancing, resource allocation, quality of service provisioning, and network security. For example, [4] studied the power control problem in a code-division multiple access (CDMA)-like system with game theory. There, each user is a player whose payoff is increasing signal-to-interference-and-noise ratio (SINR) and decreasing power level. Obviously, each user's action (increasing its transmit power) has an influence on other users' payoff and even results in a chain reaction. For example, if all other users' power were fixed, increasing one's power would increase its SINR. However, raising one's power would increase the interference seen by other users, driving their SINRs down, causing them to increase their own power levels. Game theory is a good tool for analyzing this situation.

The DCF Game

As mentioned above, when a node has data to transmit, it autonomously decides when to transmit in IEEE 802.11 DCF-based ad hoc networks. Because the wireless channel is a shared channel, the transmission of a node often interferes with those of other nodes. For example, if there are two neighboring nodes transmitting their data frames simultaneously, both transmissions will fail. Therefore, one node must compete with its neighboring nodes so that it can transmit as many packets as possible. In this section we model the IEEE 802.11 DCF with game theory and name the model the DCF game.

In the DCF game, each player (node) has two strategies: *Transmit* or *Not transmit* (i.e., wait). Figure 2 is the strategy table of the DCF game with two players (nodes 1 and 2 are contending for the channel.), where u_s is the payoff when a node transmits successfully, u_i is the payoff when a node is idle, and u_f is the payoff when a transmission fails. Even though we do not care about the real values of u_s, u_i and u_f here, there is a self-evident relation among them as follows:

$$u_f < u_i < u_s. \qquad (1)$$

This is also a two-player noncooperative game; obviously, the players in this game would prefer higher payoffs. This

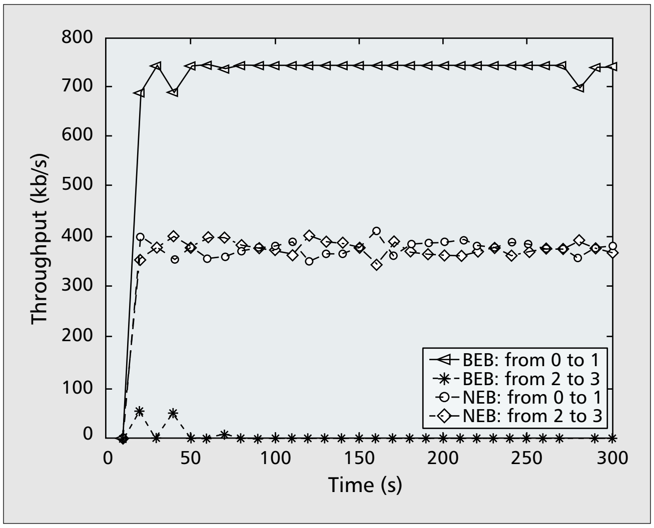

FIGURE 4. *TCP throughput with two different backoff algorithms. The first TCP session is from node 0 to 1, the second from node 2 to 3.*

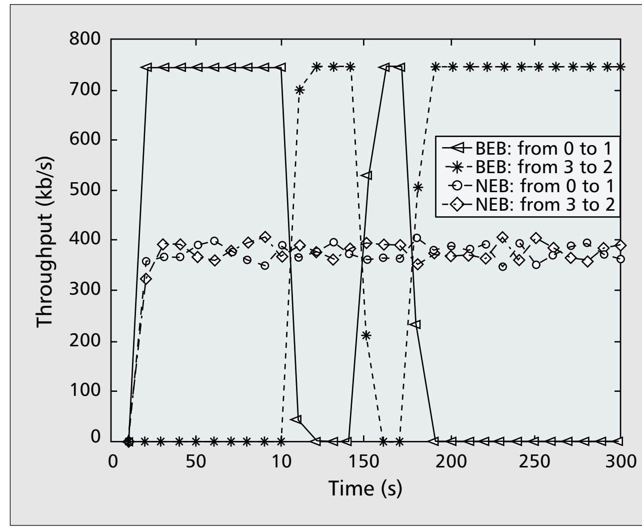

FIGURE 5. *TCP throughput with two different backoff algorithms. The first TCP session is from node 0 to 1, the second from node 3 to 2.*

game has two Nash equilibria in pure strategy: (*Transmit*, *Not transmit*) and (*Not transmit*, *Transmit*). The DCF realizes the two equilibrium strategies in the following way. When a node wants to transmit packets, it listens to the busy/idle state of the medium first. If the channel is idle for a period of time equal to a distributed interframe space (DIFS), the node transmits. Otherwise, the node does not transmit and persists in monitoring the channel until the medium is determined to be idle without interruption for a DIFS. Moreover, the DCF game has another Nash equilibrium in mixed strategy, in which each node chooses the strategy *Transmit* with probability $(u_s - u_i)/(u_s - u_f)$ and chooses the strategy *Not transmit* with probability $(u_i - u_f)/(u_s - u_f)$. The DCF realizes this mixed strategy as follows. When the channel is busy, the node persists in listening to the channel until it becomes idle for a DIFS; then the node waits a random backoff interval. The random backoff interval can be modeled by the mixed strategy.

If we analyze the values of u_s, u_i and u_f further, we find that:

- u_i indicates delay sensitivity of the traffic being transmitted. The smaller the value of u_i, the more delay-sensitive the traffic.
- u_s should be the increasing function of the length of the data frame. The longer the data packet transmitted successfully, the higher the channel utility ratio.
- u_f should be the decreasing function of the length of the data frame. A transmission failure of a long data frame does more harm to the network than that of a short frame, since a wireless node cannot sense the channel while it is transmitting.

The DCF does not consider how the priorities of different traffic affect the performance of a network; it does not consider how the lengths of different data frames affect the performance of a network either. However, we can construct different DCF game models for traffic with different priorities and different lengths by adjusting the values of u_i, u_s, and u_f accordingly, acquiring different Nash equilibria in mixed strategy and thus different random waiting intervals so that we can improve the performance of DCF (e.g., the fairness). In addition, if each node contends for the channel repeatedly and the network has multiple nodes, we need a very complicated method to determine the values of u_i, u_s, and u_f. All of these deserve to be researched further so that we can design better MAC protocols for ad hoc networks.

The Fairness Game

Fairness is an important issue for the MAC protocol when multiple nodes contend for a scarce and shared wireless channel. With fair scheduling, different flows share a wireless channel's bandwidth in proportion to their weights to provide fair and bounded delay channel accesses. The IEEE 802.11 DCF was designed to provide MAC with fairness in a best effort manner. However, in multihop ad hoc networks, much research has shown that this MAC protocol is extremely unfair when it supports TCP flows. The main reason is that the BEB algorithm always favors the latest successful nodes.

In this section we propose a simple fairness game to design a new backoff strategy to improve the fairness of the IEEE 802.11 DCF in a multihop ad hoc network as shown in Fig. 3. Note that in the DCF game above, we focus on interpreting how the sender starts to transmit the data frame in the basic scheme or the RTS frame in the RTS/CTS scheme of the IEEE DCF, but in the fairness game we focus on how to design a fair backoff algorithm to make the sender retransmit its RTS or data frame when it cannot receive the CTS or ACK from the receiver. In Fig. 3 each node communicates with an identical half duplex wireless radio modeled after the commercially available 802.11-based WaveLan wireless radios with a bandwidth of 2 Mb/s and a nominal transmission radius of 250 m; the distance between any two neighboring nodes is equal to 200 m. Therefore, each node can communicate only with its neighboring nodes. There are two TCP sessions; the first is between 0 and 1, and the second between 2 and 3.

Since nodes 0 and 1 constitute a TCP session, the unsuccessful transmission of either of them will do harm to the TCP performance. Therefore, in the fairness game they form a coalition to contend for the wireless channel with the coalition formed by nodes 2 and 3. However, as the designers of the MAC protocol, we expect that not only can the two coalitions fully utilize the wireless channel, but they can also fairly share the channel. In other words, we expect the individual rationality of each coalition to be consistent with the collective rationality of both coalitions. An approach to consistency is that each coalition broadcasts its local noise-to-signal ratio (NSR), which is the sum of the NSR of each node in the coalition. The NSR of a node is defined as the reciprocal of the ratio of signal to noise and can be acquired at the physical layer when collisions occur. It is self-evident that the larger the NSR of a coalition, the smaller the the possibility that the TCP traffic of the coalition can be transmitted successfully. Being dependent on the NSR of its local coalition, NSR_{local}, and the NSR of the

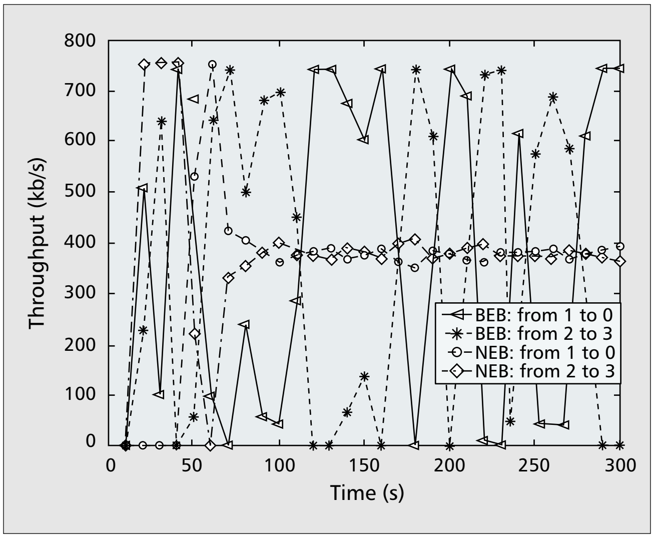

FIGURE 6. *TCP throughput with two different hackoff algorithms. The first TCP session is from node 1 to 0, the second from node 2 to 3.*

neighbor coalition, $NSR_{neighbor}$, we can modify the backoff algorithm of the IEEE 802.11 DCF as follows. When a collision occurs, each node in a coalition will generously and considerately adopt the following backoff strategy:

- If $NSR_{local} \leq NSR_{neighbor}$, then $CW = \lfloor CW \cdot Random[3, 4] \rfloor$;
- Else $CW = \lfloor CW \cdot \text{Random}[O, 3] \rfloor$,

where $\lfloor x \rfloor$ is the largest integer that is not more than x, and $Random[x, y]$ denotes a random number uniformly distributed on the close interval $[x, y]$. An important fact behind this strategy is that two nodes of a coalition have the same NSR_{local} and the same $NSR_{neighbor}$; therefore, they make a binding commitment and thus play cooperative games between them. And nodes of different coalitions play noncooperative games among them.

Obviously, this is a Nash equilibrium strategy. Because $NSR_{local} \leq NSR_{neighbor}$ comes into existence for one coalition, $NSR_{local} > NSR_{neighbor}$ also comes into existence for the other coalition. Therefore, given that the nodes in one coalition set a bigger *CW*, the best strategy for the nodes in the other coalition is to set a smaller *CW* to make use of the channel effectively. On the contrary, given that the nodes in one coalition set a smaller *CW*, the best strategy for the nodes in the other coalition is to set their *CW* bigger to decrease collisions. We name this new backoff algorithm the Nash equilibrium backoff (NEB) algorithm.

To evaluate the performance of the fair game strategy, we present three different simulation experiments for the proposed NEB and BEB algorithms. Each simulation has two different TCP connections. These studies are conducted using the ns2 simulator [5]. All results are based on TCP-Reno, which is now the most popular TCP version; dynamic source routing (DSR) is the routing protocol used for each experiment. The TCP packet size is 1460 bytes, and the TCP maximum window *wnd* is 1. CW_{min} and CW_{max} are set to 15 and 2047, respectively. Each simulation runs for 300 s; both TCP sessions start at 10 s simultaneously. We define TCP throughput as the packet size in bits received by the TCP receiver per second.

Figure 4, 5, and 6 show the TCP throughput with two different backoff algorithms. The plotted values of the throughput are measured over a 10 s interval. From the simulation results, we can observe that the BEB algorithm is very unfair to the two TCP flows, but the NEB algorithm can improve the TCP fairness almost perfectly and even gain a little throughput advantage (about 12 kb/s) over the BEB algorithm. These results are what we need indeed.

Conclusions

Game theory, the study of how players should rationally play games, is a powerful tool in many areas, such as war, politics, economics, sociology, psychology, biology, communications, networking, and so on, where conflict and cooperation exist. In this article we propose a simple game model to interpret the IEEE 802.11 DCF mechanism and also point out some directions that deserve study. In addition, by designing a simple Nash equilibrium backoff strategy, we present a fairness game model that could improve TCP fairness almost perfectly. Our results show that game theory is an appropriate tool to research and analyze the performance of wireless ad hoc networks. Of course, most networks are enormously complex, it is usually impossible to delineate all conceivable strategies and to say what outcomes they lead to, and it is not easy to assign payoffs to any given outcome. However, by building and analyzing a simple game that models some important features of the complex network, we can gain insight into the original situation, which is just what we expect in many cases.

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