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Using Incompletely Cooperative Game Theory in Mobile Ad Hoc Networks

Liqiang Zhao
State Key Laboratory of Integrated Services Networks
Xidian University
Xi'an, Shaanxi, 710071, China
e-mail: lqzhao@mail.xidian.edu.cn

Jie Zhang
Dept. of Computing and Information Systems
University of Bedfordshire
Luton, LU1 3JU, UK
e-mail: jie.zhang@beds.ac.uk

Kun Yang
Department of Electronic Systems Engineering
University of Essex
Colchester, C04 2SQ, UK

Hailin Zhang
State Key Laboratory of Integrated Services Networks
Xidian University
Xi'an Shaanxi, 710071, China

***Abstract*—Recently, game theory becomes a useful and powerful tool to research mobile ad hoc networks (MANETs). Wireless LANs (WLANs) can work under both infrastructure and ad hoc modes, and are the most widely used MANETs. In this paper, we propose a novel concept of incompletely cooperative game theory and use it to improve the performance of WLANs. In this game, firstly, each node estimates the current state of the game (i.e., the number of competing nodes) by detecting the channel. Secondly, each node changes its equilibrium strategy by tuning its local contention parameters based on the estimated game state. Finally, the game is repeated finitely to get the optimal performance. Our simulation results show that the incompletely cooperative game can increase system throughput, and decrease delay, jitter and packet-loss-rate.**

Keywords-Game Theory; Mobile Ad Hoc Network; Wireless LAN; MAC

I. INTRODUCTION

Mobile ad hoc networks (MANETs) play an increasingly important role in many environments, e.g., in collaborative and distributed computing, disaster recovery, crowd control, and search-and-rescue. Wireless LANs (WLANs) have been widely used under both infrastructure and ad hoc modes as one of the essential technologies to provide broadband wireless access, and the performance analysis and improvement of WLANs have attracted a lot of research interests. IEEE 802.11 is one of the most influential WLAN standards, and its basic medium access control (MAC) protocol is called distributed coordination function (DCF) [1]. Currently, DCF has been the de facto MAC standard of MANETs, widely used in almost all of the testbeds and simulations for MANET research, although there are many MAC protocols of MANETs and DCF is not the latest one.

In DCF, there are no central nodes (e.g., base stations or access points) to control nodes' channel access, and all nodes transmit their data frames competitively. The channel access of each node has a direct influence on its neighboring nodes. The interactions give us an intuition that game theory would be a very good tool to analyze and improve the performance of MANETs [2-15], especially the MAC protocols, such as Aloha [3-8] and DCF [11][13]. When using game theory in MANETs, we must consider the characteristics of DCF. [13] presents a simple Nash equilibrium backoff strategy to resolve the so-called unfairness problem in WLANs. However, in [13] each node has to broadcast its local signal-to-noise ratio (SNR) periodically. It is impossible to be implemented in current WLANs. Hence, in this paper we propose a novel concept of incompletely cooperative game theory (i.e., a finitely repeated dynamic game of incomplete information) that can improve throughput and decrease delay, jitter and packet-loss-rate. In this game, each node adjusts its equilibrium strategy to the estimated game state, i.e., the number of competing nodes.

The rest of this paper is organized as follows. Game theory and DCF are introduced in section II respectively. In section III, we propose the incompletely cooperative game to improve the performance of DCF. In section IV, simulation studies are carried out to evaluate the performance of the game. The concluding remarks are given in Section V.

II. PRELIMINARIES

A. Description of Game Theory

Game theory is a powerful tool to study situations of conflict and cooperation, which is concerned with finding the best actions for individual decision makers (i.e., players) in these situations and recognizing stable outcomes. Games may generally be categorized as non-cooperative and cooperative games. Non-cooperative game theory is concerned with the analysis of strategic choices and explicitly models the decision making process of a player out of his/her own interests. Unlike in non-cooperative games, in cooperative games, the players can make binding commitments. Game theory received special attention in 1994 with the award of the Nobel prize in economics to John Nash, John Harsanyi, and Reinhard Selten s) for their great contributions mainly in non-cooperative games. According to whether the players' moves are simultaneous or not, non-cooperative games can be divided into two categories: static and dynamic games. In the static game, players make their choices of strategies simultaneously, without knowledge of what the other players are choosing. In the dynamic game, there is a strict order of play. Players take turns to make their moves, and they know what the other players have done beforehand. According to whether the players have full information of all payoff-relevant characteristics about the opponents or not, the non-cooperative 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 I shows four kinds of non-cooperative games and corresponding equilibrium concepts.

Tab. I. Categories of non-cooperative games and corresponding equilibria

	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) Kreps and Wilson (1982) Fudenberg and Tirole (1991)

B. Description of DCF

DCF is a random access scheme, based on carrier sense multiple access with collision avoidance (CSMA/CA). A node with a new packet to transmit monitors the channel activity. If the channel is idle for a period of time called distributed interframe space (*DIFS*), the node transmits. Otherwise, the node persists in monitoring the channel until it is measured idle for a *DIFS*. At this point, the node generates a random slotted backoff interval before transmitting. The slot time size is called *aSlotTime*. DCF adopts an exponential backoff scheme. At each packet transmission, the backoff time is uniformly chosen in the range [0, *CW*-1]. At the first transmission attempt, the contention window, *CW*, is set equal to a value CW_{min} called the minimum contention window. After each unsuccessful transmission, *CW* is multiplied by σ up to the maximum value $CW_{max} = \sigma^m CW_{min}$. The value σ called persistent factor is fixed as 2, and m is called the maximum backoff stage, and CW_{max} is called the maximum contention window. Once *CW* reaches CW_{max}, it will remain at the value until the packet is transmitted successfully or the retransmission time reaches retry limit (r). While the limit is reached, retransmission attempts shall cease and the packet shall be discarded.

III. DESCRIPTION OF INCOMPLETELY COOPERATIVE GAME THEORY

Recent research shows that the DCF backoff mechanism has one main drawback: in a high load network the increase of the value of *CW* is obtained at the cost of continuous collision after a successful transmission because no state information indicating the actual contention level is maintained. Incompletely cooperative game theory can solve this problem by estimating the current state of the game (i.e., actual system state), and scheduling each node's equilibrium strategy based on the estimated game state.

A. Characteristics of incompletely cooperative game theory

The incompletely cooperative game has three characteristics. Firstly, in DCF, nodes cannot directly exchange the game state in time, such as their local SNRs [13]. However, each node can estimate the game state by detecting the channel. After detecting the channel for a long time, the estimated game state is accurate enough. Of course, as the game state is always variable, it may be impossible for a node to always obtain an accurate game state in time. Secondly, each node can obtain incompletely information (not all the information) of the game state. Finally, the incompletely cooperative game is a finitely repeated game rather than an infinitely repeated one.

The incompletely cooperative game is a stochastic game; each slot corresponds to one game state. In each slot, on the one hand, nodes transmit their packets; on the other hand, they estimate the current game state from the past states. After estimating the actual game state, nodes tune their equilibrium strategies. Due to the variable game state, the equilibrium strategy of each node is always variable. In the incompletely cooperative game, players make their choices of strategies simultaneously. Although they do not know what the other players are choosing now, they can predict the others' actions according to what has happened.

B. Game state

Several performance evaluation studies show that the performance of DCF is very sensitive to the number of nodes competing on the channel, i.e., the number of nodes that are simultaneously trying to send a packet on the shared medium [16-17]. This information cannot be retrieved from DCF operation. For simplicity, in this paper, the game state is the number of competing nodes.

C. Estimation of the game state

Analysis results show that the number n of competing nodes is the function of frame collision probability of a competing node (p).

In the fundamental assumption that, regardless of the number of retransmission suffered, the probability p is constant and independent at each transmission attempt, it has been shown in [16] that the probability τ that a node transmits in a randomly chosen slot can be expressed as a function of p as:

$$\tau = \frac{2(1-\sigma p)}{(1-\sigma p)(CW_{\min}+1) + pCW_{\min}\left(1-(\sigma p)^m\right)} \tag{1}$$

and that the probability p can be expressed as a function of τ and n as:

$$p = 1-(1-\tau)^{n-1} \tag{2}$$

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Substituting τ, as expressed by (1), into (2), and solving the equation with respect to n, we obtain:

$$
\begin{aligned}
n &= f(p) \\
&= 1 + \frac{\log(1-p)}{\log\left(1 - \dfrac{2(1-\sigma p)}{(1-\sigma p)(CW_{\min}+1) + pCW_{\min}\left(1-(\sigma p)^m\right)}\right)}
\end{aligned}
\tag{3}
$$

The above equation provides an explicit expression of n versus the probability p and contention parameters, such as CW_{min}, m, and σ.

Since the probability p can be independently measured by each node by simply monitoring the channel activity, it follows that each node can estimate the value n.

Moreover, Bianchi [20] provided two perfect run-time estimation mechanisms, i.e., auto regressive moving average (ARMA) and Kalman Filters.

Please note that (1) is based on an assumption that the retry limit is neglected and the packet will be retransmitted infinitely until it is transmitted successfully. If the retry limit is considered, (1) can be modified as (4).

$$
\tau = \begin{cases}
\dfrac{2(1-2p)(1-p)^{m+1}}{CW_{\min}\left(1-(2p)^{m+1}\right)(1-p) + (1-2p)\left(1-p^{m+1}\right)} & r \le m \\[2ex]
\dfrac{2(1-2p)(1-p)^{r+1}}{CW_{\min}\left(1-(2p)^{m+1}\right)(1-p) + (1-2p)\left(1-p^{r+1}\right) + CW_{\min}2^m p^{m+1}(1-2p)\left(1-p^{r-m}\right)} & r > m
\end{cases}
\tag{4}
$$

D. Equilibrium Strategy

In the incompletely cooperative game, each player has two possible actions: *Transmit* or *Wait*. An equilibrium strategy is an infinite vector of transmit probabilities, (p_1, p_2, …), such that p_n maximizes each player's utility given that there are currently n competing nodes. Fig. 1 is the strategy table with 2 players, where μ_s is the payoff when a player transmits successfully, μ_i is the payoff when a player is idle, μ_f is the payoff when a transmission fails, and $\mu_f < \mu_i < \mu_s$,. The players in this game use (p_1, p_2, …) to determine their transmit probabilities to get higher payoffs.

In [13], a player is a node contending for the channel. As each node contends for the channel repeatedly and the network has multiple nodes, a very complicated method is needed to determine the strategy. However, [13] did not provide any solutions. Please note that in this paper a player is not always a node. If we analyze the equilibrium strategy of node a, Player 1 is node a, and Player 2 (i.e., its opponents) is all the other (n-1) nodes (i.e., node b, c, etc).

		Player 2 (all the other n-1 nodes)	
		Wait	Transmit
Player 1 (node a)	Wait	(μ_i,μ_i)	(μ_i,μ_s)
	Transmit	(μ_s,μ_i)	(μ_f,μ_f)

Fig. 1. Incompletely cooperative game model with n nodes

When using game theory in the slotted Aloha MAC protocol, [3-6] proposed an explicit formulation for the strategy under the assumption that the change of the game state has no impact on the existence of an equilibrium. However, it is unsuitable for MANETs, and DCF is too complicated to propose an explicit formulation. In DCF, the value of transmit probabilities can be changed by tuning contention parameters, such as the minimum contention window (CW_{min}), the maximum backoff stage (m), the maximum contention window (CW_{max}), persistent factor (σ) and retry limit (r) [18-19]. For simplicity, in this paper we tune only one contention parameter, CW_{min}.

If a player has packets to send, before she contends the channel to transmit any packets, she predicts the game state, i.e., the number n of competing nodes. After getting the game state, she tunes CW_{min} as follows:

$$
CW_{\min} = \lfloor n \times rand(7,8) \rfloor \tag{5}
$$

where rand (x, y) returns a random value between x and y, and $\lfloor z \rfloor$ is the largest integer that is not more than z. Research results show that the optimal value of CW_{min} is dependent on the number n [16] [20]. The ratio of the optimal CW_{min} to n is about from 7 to 8 [22-23]. For simplicity, we can obtain the value of CW_{min} from the above equation. The following simulation results show that the above equation is accurate enough to compute CW_{min}. The player with different CW_{min} has different transmission probabilities and collision probabilities. The optimal CW_{min} corresponds to the smallest collision probability.

An important fact behind this strategy is that different nodes may have different CW_{min} and transmit probabilities in a given slot as they may get different estimated values of n. Each node's goal is not to maximize her payoff in a single slot, but to maximize her expected payoff over the slots from the beginning until she transmits successfully. Since Player 1 begins to contend the channel to transmit her packets, before transmitting successfully, she keeps estimating the game state. The game state is always variable due to three reasons. Firstly, some other nodes may leave the game, for example, as transmitting successfully. Secondly, new arrival nodes may join the game. Finally, as Player 1 enters the game, the game state is changed, and Player 2 (i.e., the other nodes) will detect this variation and adapt their equilibrium strategies to the current game state. During the transmission, after getting the game state, Player 1 keeps adjusting her local contention parameters to the current game state.

IV. SIMULATION RESULTS

To evaluate incompletely cooperative game theory, the following simulations are made in an ideal channel with none hidden terminals and capture. The values of the parameters used to obtain numerical results for simulations are specified in IEEE 802.11b protocol [21]. The channel rate is fixed at 11 Mb/s, m=5, and r=7. The packets will be discarded only due to the re-transmission time reaches the retry limit, and do not consider the delay limit.

Assume the number of nodes increases from 10 to 90 in a step of 20, and every node always has packets to send under the saturation case [20]. By detecting the channel, each node estimates the game state, i.e., the number of competing nodes, and then tunes its contention parameter CW_{min}. For simplicity, assume each node can obtain the number of competing nodes timely and accurately. The saturated throughput, delay, jitter and packet-loss-rate are shown in Fig. 2-5.

Fig. 2 shows that the saturation throughput in the incompletely cooperation game is higher than that in DCF, especially when the number of nodes is large. Due to collision, the throughput in DCF decreases when the number of nodes increases. And the throughput in the incompletely cooperative game almost keeps constant, as each node can adapt to the variable game state and choose the corresponding equilibrium strategy.

Fig. 3 shows that the saturation delay in the incompletely cooperative game is lower than that in DCF. In DCF each node gets the optimal *CW* after several collisions. In the incompletely cooperative game each node gets the optimal *CW* after estimating the game state.

Fig. 4 shows that the saturation jitter in the incompletely cooperative game is much lower than that in DCF, especially when the number of nodes is large.

Fig. 5 shows that the saturation packet-loss-rate in the incompletely cooperative game is much lower than that in DCF. In the incompletely cooperative game, the packet-loss-rate is zero, which is very attractive.

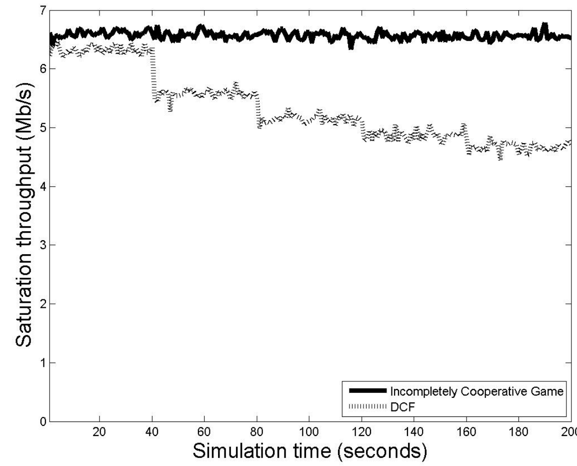

Fig. 2. Throughput under saturated conditions

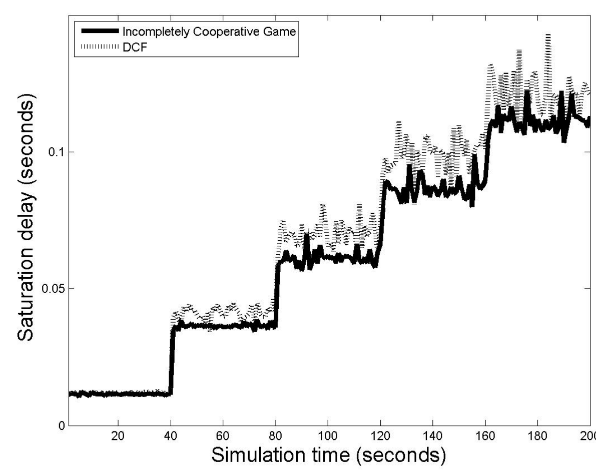

Fig. 3. Delay under saturated conditions

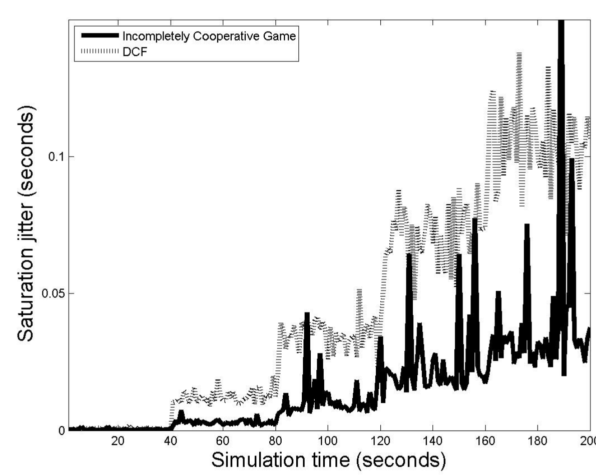

Fig. 4. Jitter under saturated conditions

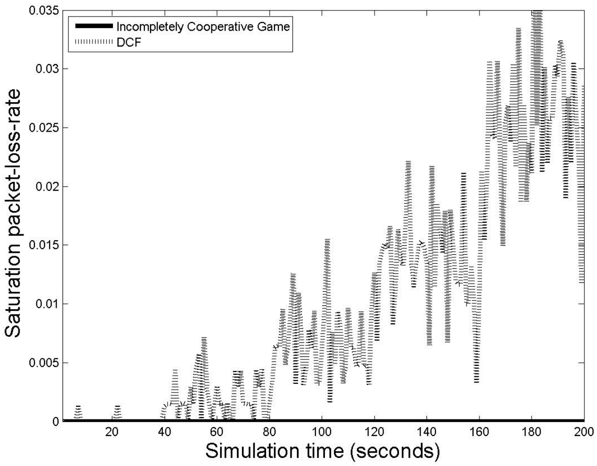

Fig. 5. Packet-loss-rate under saturated conditions

Suppose there are 50 nodes and each node generates new packets under a Poisson process in unsaturated cases. The packet arrival rate is initially set to be lower than the saturation case, and it is subsequently increased so that, at the end of the simulation time, all nodes are almost in saturation conditions. The throughput, delay, jitter and packet-loss-rate are shown in Fig. 6-9.

Fig. 6-9 shows that the performance of the incompletely cooperative game is better than that of DCF when the network load is heavy.

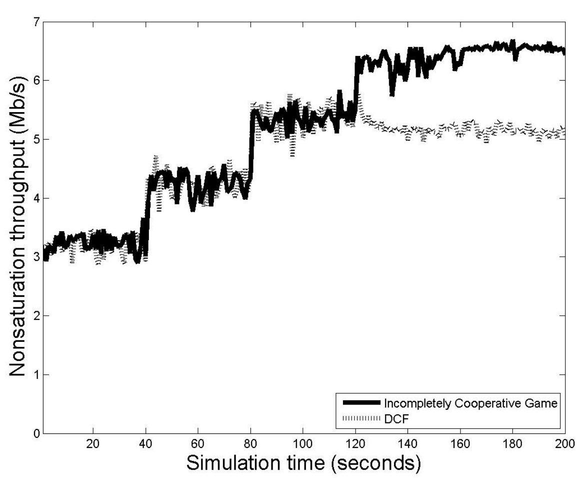

Fig. 6. Throughput under unsaturated conditions

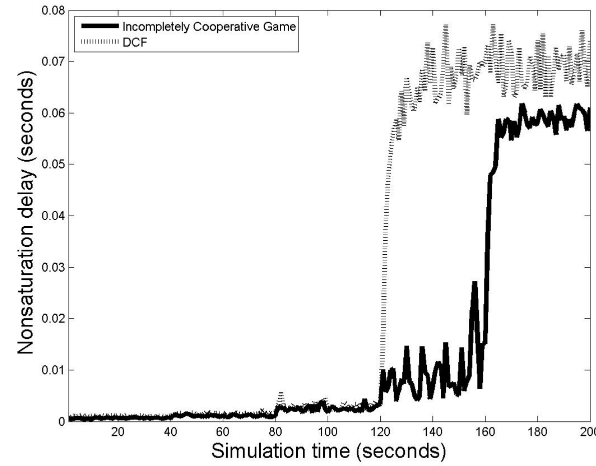

Fig. 7. Delay under unsaturated conditions

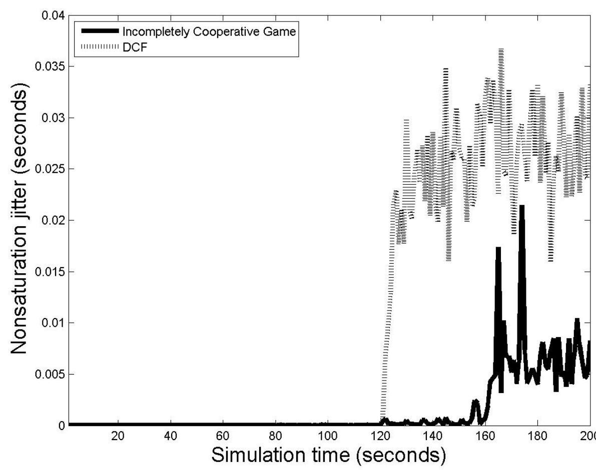

Fig. 8. Jitter under unsaturated conditions

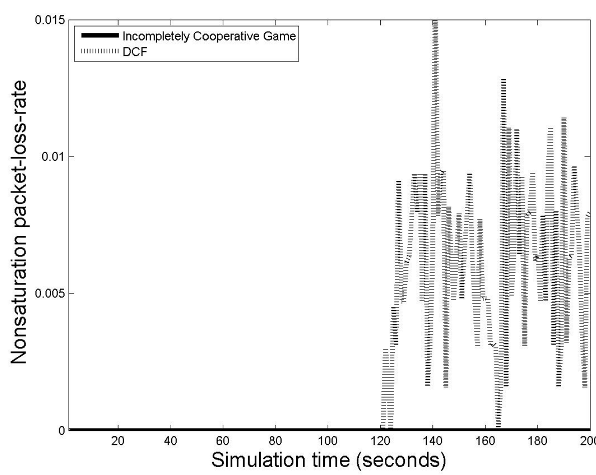

Fig. 9. Packet-loss-rate under unsaturated conditions

V. CONCLUSIONS

In this paper we propose the incompletely cooperative game that can improve the system performance of MANETs. In this game, firstly, each player estimates the game state, i.e., the number of competing nodes. Secondly, based on the estimated game state, each player tunes its equilibrium strategy by changing its local contention parameters. Finally, the game is repeated finitely to get the optimal performance. Our results show that the incompletely cooperative game is an appropriate tool to improve the performance of MANETs.

We are carrying researching in the following fields. Firstly, as incompletely cooperative game theory is a novel concept and there is no such theory in current game theory textbooks or articles, we shall develop its equilibrium and utility function in detail and justify it mathematically. Secondly, we assume that each node can obtain the number of competing nodes timely and accurately, which simplifies the problem very much. Although several articles have discussed the estimation mechanism, such as ARMA and Kalman Filters, they are based on several strict assumptions and too complex to be implemented, the problem remains unsolved. We are carrying research on a simple algorithm to estimate the game state.

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