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Using Incompletely Cooperative Game Theory in Wireless Sensor Networks

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***Abstract*—In WSNs, energy conservation is the primary goal, while throughput and delay are less important. So used energy is traded for throughput and delay. In this paper, a novel concept of incompletely cooperative game theory is used in WSNs to simultaneously achieve all the goals. In the game, each node adjusts its equilibrium strategy to the estimated game state. After discussing the utility function of the game, the equilibrium strategy for the game in WSNs is presented, Moreover, a simplified game-theoretic MAC protocol (G-MAC) is provided for WSNs, by using an auto degressive backoff mechanism, which is easy to be implemented. Simulation results show that the incompletely cooperative game can increase system throughput, and decrease delay and packet-loss-rate, while still maintaining reasonable energy consumption, and that G-MAC supports the game effectively.**

Keywords-game thoery; wireless sensor network; MAC

I. INTRODUCTION

As an emerging technology, Wireless Sensor Networks (WSNs) have a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration. Performance analysis and improvement of WSNs, especially its Medium Access Control (MAC) protocols, have attracted much research interests. Traditional MAC protocols for wireless ad hoc networks are designed to maximize throughput and minimize delay. As sensor nodes are generally battery-operated, to design a good MAC protocol for WSNs, the first attribute that has to be considered is energy consumption [1]. Other important attributes (such as throughput and delay) are generally the primary concerns in traditional wireless ad hoc networks, but in WSNs they are secondary.

Current MAC designs for WSNs can be broadly divided into scheduling-based, collision free, contention-based [2-6] and hybrid schemes. Scheduling-based (e.g., TDMA-based) protocols have a natural advantage of energy conservation compared to contention-based protocols, because the duty cycle of the radio is reduced and there is no contention-introduced overhead and collisions. However, maintaining a TDMA schedule (e.g., time synchronization) in wireless ad hoc networks is not an easy task and will result in complexity in the nodes. Contention free protocols can decrease energy consumption by decreasing collision and have the potential to increase throughput and decrease delay. However, contention free protocols require multiple independent radios and/or channels and are too complex to implement in sensor nodes. The hybrid protocol (e.g., Z-MAC [7]) combines the strengths of TDMA and CSMA. However, current hybrid protocols have to further offset the weakness of the incorporated protocols. IEEE 802.11 Distributed Coordination Function (DCF), the basic MAC protocol in Wireless LANs (WLANs), is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), one of typical contention-based protocols. Currently, CSMA/CA has been the de facto MAC standard for wireless ad hoc networks, widely used in almost all of the testbeds. Moreover, low-power, low-rate Wireless PANs (WPANs) such as IEEE 802.15.4 utilizes CSMA/CA too. However, the energy consumption using CSMA/CA is very high when nodes are in an idle mode. It is mainly called problem of idle listening. CSMA/CA-based S-MAC [2] is explicitly designed for WSNs to solve this problem. The basic idea of S-MAC is that used energy is traded for throughput and delay by introducing an active/sleep duty period. Some researchers are attempting to improve the performance of S-MAC [3-6].

Recently, game theory becomes a very good tool to analyze and improve the performance of contention-based protocols [8-11]. [8-11] propose game-theoretic approaches to solve the problem of security, query routing, and power control respectively in distributed sensor networks.

When using game theory in WSNs rather than economics, much attention should be paid to the natural characteristics of WSNs. For example, explicit cooperation among nodes is clearly impractical in WSNs as it causes additional energy and bandwidth consumption. [12] briefly presents a novel concept of incompletely cooperative game theory to improve the performance of DCF without any explicit cooperation among nodes. [13] provides an auto degressive backoff mechanism to implement the game in current WLANs. However, both have not been used in WSNs.

In this paper, the game will be elaborated in much greater details, and the preliminary results presented in [12-13] will be substantially extended in order to be used in WSNs, e.g., the equilibrium strategy of the game for WSNs.

The rest of this paper is organized as follows. Some existing energy-saving solutions are introduced in section II. In section III, after discussing the equilibrium strategy of the game for WSNs, the game is introduced into WSNs to improve the performance of existing contention-based MAC protocols. In section IV, a simplified game-theoretic MAC protocol (G-MAC) is presented to implement the game in WSNs. In section V, simulation studies are carried out to evaluate the performance of the game and G-MAC. The concluding remarks are given in Section VI.

II. CONTENTION-BASED MAC PROTOCOLS

CSMA/CA uses an acknowledgment (ACK) mechanism for verifying successful transmissions and optionally, an RTS/CTS handshaking mechanism for decreasing collisions overhead. In both cases an exponential backoff mechanism is used. Before transmitting, a node generates a random slotted backoff interval, and 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 doubled up to the maximum value $CW_{max} = 2^m CW_{min}$. The value m is called the maximum backoff stage, and CW_{max} is 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 will cease and the packet will be discarded.

Most energy in CSMA/CA is wasted by the idle listening. Since a node does not know when it will be receiving a packet from one of its neighbors, it must keep its radio in the receiving mode at all times. Many measurements have shown that idle listening consumes 50-100% of the energy required for receiving.

In S-MAC, each node periodically sleeps, wakes up, listens to the channel, and then returns to sleep [2]. During the sleeping period, the node turns off its radio to preserve energy. During the listening period, it can communicate with its neighbors and send the messages queued during the sleeping period in the standard CSMA/CA mode. S-MAC essentially trades used energy for throughput and delay. Throughput is reduced because only the listening period is used for communication. Delay increases because a message-generating event may occur during the sleeping time. In that case, the message will be queued until the start of the next listening period.

To handle load variations in time and location, T-MAC introduces an adaptive duty cycle by dynamically ending the listening period [3]. To achieve a low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening [4]. Based on synchronized preamble sampling, WiseMAC achieves significantly lower power consumption for the same delay as the power management protocol used in the IEEE 802.15.4 ZigBee standard [5]. DSMAC adjusts multiple duty cycles automatically, based on the measurement of the energy consumption level and delay [6].

In a word, the basic idea of contention-based MAC protocols in WSNs (e.g., S-MAC) is to trade energy consumption for throughput and delay. That is to say, if we want to eat the cake and still have it, then one way out is to sacrifice throughput and delay for energy consumption.

III. INCOMPLETELY COOPERATIVE GAME THEORY

A. *Framework of Incompletely Cooperative Game Theory*

The incompletely cooperative game can be classified as a stochastic game, which starts when a new packet arrives at the node's transmission buffer and ends when the packet is transmitted successfully or discarded. Each game process includes many timeslots and each timeslot corresponds to one game state. In each timeslot, each player (i.e., node) estimates the current game state based on what happened in the past timeslots. After estimating the current game state, the player adjusts its own equilibrium strategy by tuning its local contention parameters. Then all the players take actions simultaneously, i.e., transmitting their packets, listening or sleeping. Although the player does not know which action the other nodes (i.e., its opponent) are taking now, it can predict its opponent' actions according to what has happened.

In the game, each player takes a distributed approach of detecting and estimating the current game state, and tuning its local contention parameters to the estimated game state. As seen in Fig. 1, the framework of the game consists of three major components, a detector, an estimator and an adjustor. The first component, the detector, detects and records the experienced PHY-specific information, such as Signal-to-Noise Ratio (SNR), and MAC-specific information, such as frame transmission probability (τ), frame conditional collision probability (p), and TCP/IP-specific information, such as TCP Datagram Loss Ratio (DLR). The second component, the estimator, uses the above measurements to estimate the current game state, such as the number of competing nodes (n). The third component, the adjustor, makes a decision according to which strategy the player transmits its packets, and implements the optimal strategy by tuning contention parameters, such as TCP sliding window, MAC contention parameters [16], and transmission power.

Such cross-layer characteristics [17] imply that to obtain the game state and to tune the equilibrium strategy in each timeslot, cross-layer detection, cross-layer estimation and cross-layer adjustment are needed. The term "cross-layer" in the incompletely cooperative game means that the knowledge of the PHY, MAC and TCP/IP layers is used by the detector, estimator and adjustor, to calculate the game state and implement the optimal strategy.

B. *Equilibrium Strategy of Incompletely Cooperative Game Theory*

In economics, normally, the optimal target of the player is to maximum its own profits. However, in WSNs, the target of each player is to maximum the system performance under the limited energy consumption.

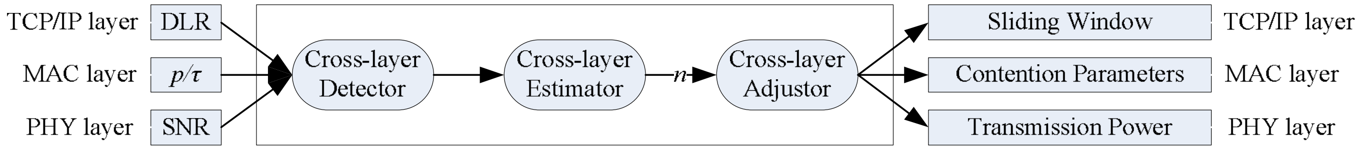

Figure 1. Framework of incompletely cooperative game theory

Player 1 (node i)	Player 2/Opponent (all the other n nodes): Successful Transmission	Failed Transmission	Listening	Sleeping
Transmitting	$(c_f, \bar{c}_f)$		$(c_s, \bar{c}_i)$	
Listening	$(c_i, \bar{c}_s)$	$(c_i, \bar{c}_f)$	$(c_i, \bar{c}_i)$	
Sleeping				$(c_w, \bar{c}_w)$

Figure 2. Incompletely cooperative game model of n+1 nodes

$$\begin{cases} s_i^* = \arg\max_{s_i} \bar{\mu}_i \mid \left(e_i < e_i^*\right) = \arg\max_{(w_i,\tau_i)} \left(\left(1-w_i\right)\left(\left(1-\bar{\tau}_i\right)\bar{c}_i + \bar{\tau}_i\left(1-\bar{p}_i\right)\left(1-\tau_i\right)\bar{c}_s + \bar{\tau}_i\left(1-\bar{p}_i\right)\tau_i\bar{c}_f + \bar{\tau}_i\bar{p}_i\bar{c}_f\right) + w_i\bar{c}_w\right) \mid \left(e_i < e_i^*\right) \\ \bar{s}_i^* = \arg\max_{\bar{s}_i} \mu_i \mid \left(\bar{e}_i < \bar{e}_i^*\right) = \arg\max_{(\bar{w}_i,\bar{\tau}_i)} \left(\left(1-w_i\right)\left(\left(1-\tau_i\right)c_i + \tau_i\left(1-\bar{\tau}_i\right)c_s + \tau_i\bar{\tau}_i c_f\right) + w_i c_w\right) \mid \left(\bar{e}_i < \bar{e}_i^*\right) \end{cases}. \quad (1)$$

$$CW_{\min} = \begin{cases} \max\left(CW_{\min}, CW/2\right) & \text{The previous packet is transmitted successfully} \\ CW_{\max} & \text{The previous packet is discarded} \end{cases}. \quad (4)$$

In the incompletely cooperative game, the utility function of the player (i.e., node i), $\mu_i = f_i\left(s_i, \bar{s}_i\right)$. The strategy of the player, s_i, includes three possible actions: *transmitting, listening* or *sleeping*. The strategy profile of its opponent (i.e., all the other n neighbors), $\bar{s}_i = \left(s_1, s_2, ..., s_{i-1}, s_{i+1}, ..., s_n, s_{n+1}\right)$. Similarly, the utility function of its opponent, $\bar{\mu}_i = f_i\left(\bar{s}_i, s_i\right)$.

In many game-theoretic models, a player is a single node contending for the channel. As there may be many nodes in a WSN and each node may contend for the channel repeatedly, a very complicated method is needed to determine the strategy. Hence, in the game, a player is not always a single node. If analyzing the equilibrium strategy of node i, Player 1 is node i, and Player 2 (i.e., its opponent) is all the other n nodes. In fact, it is possible for Player 1 to estimate Player 2's game state, and difficult for Player 1 to estimate the states of each node in Player 2.

Player 2 includes four possible actions: s*uccessful transmission*, *fail transmission, listening* or *sleeping*. Fig. 2 is the strategy table with 2 players (i.e., n+1 nodes), where c_i and $\bar{c}_i$ are the payoff when Player 1 and Player 2 listen respectively, c_s and $\bar{c}_s$ are the payoff when they transmit successfully respectively, c_f and $\bar{c}_f$ are the payoff when they fail respectively, c_w and $\bar{c}_w$ are the payoff when they sleep respectively.

Hence, the optimal response strategy of the two players under the limited energy consumption is shown in (1), where w_i is the sleeping probability of the two players, τ_i and $\bar{\tau}_i$ are the transmission probability of the two players respectively, and $\bar{p}_i$ is the conditional collision probability of Player 2, and e_i, e_i^*, $\bar{e}_i$ and $\bar{e}_i^*$ are the real energy consumption and the energy limit of the two players respectively.

For simplicity, assume that the probability of the following two cases is zero: firstly, Player 1 transmits or listens when Player 2 is sleeping; secondly, Player 2 transmits or listens when Player 1 is sleeping. That is to say, the game needs some synchronization, but that is not as critical as TDMA-based protocols, as the time scale is much larger [2].

Obviously, Player 1 changes its sleeping and transmitting probability not to obtain its own optimal utility (μ_i^*), but to help Player 2 to achieve the optimal utility ($\bar{\mu}_i^*$); vice verse. Hence, it indicates that all the nodes play the cooperative game based on the estimated game states. On the other hand, the two players get the optimal utility under one condition, the limit of energy consumption. It indicates that all the nodes play the conditional game.

C. Incompletely Cooperative Game Theory in WSNs

However, the incompletely cooperative game is too complex to propose an explicit formulation for its utility function. Hence, a simple method is presented in the following.

Time is divided into super-frames and every super-frame has two parts: an active part and a sleeping part. During the sleeping part, each player turns off its radio to preserve energy. During the active part, the player contends for the channel according to the game, i.e., it estimates the current state of the game (e.g., the number of its opponent n), and adjusts its equilibrium strategy (e.g., the minimum contention window CW_{min}) to the estimated game state.

[14] shows that the number of its opponent n is a function of frame collision probability (p) and transmission probability (τ) of the player, as follows:

$$p = 1 - (1-\tau)^n \Rightarrow n = 1 + \frac{\log(1-p)}{\log(1-\tau)}. \tag{2}$$

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

As stated above, in the active part, each node has to always monitor the channel in order to receive any possible packets from its neighboring nodes to itself. So this estimation mechanism will not cause much more additional energy consumption.

Moreover, based on (2), [15] provides two perfect run-time estimation mechanisms, i.e., auto regressive moving average (ARMA) and Kalman Filters.

In the game, the value of the transmitting probability can be changed by tuning contention parameters, such as the minimum contention window (CW_{min}), the maximum contention window (CW_{max}), arbitrary interface space (AIFS), transmission opportunity (TXOP), etc [16]. For simplicity, in this paper after estimating the number n, the player only tunes its local CW_{min} as follows:

$$CW_{\min} = [n \times rand(7,8)]. \tag{3}$$

where rand (x, y) returns a random value between x and y, and [z] is the largest integer that is not more than z. [11] and [14] show that the ratio of the optimal CW_{min} to n is about from 7 to 8.

IV. A SIMPLIFIED GAME-THEORETIC MAC PROTOCOL FOR WSNS

The key problem in the incompletely cooperative game is how to estimate the game state accurately and timely.

[18] shows that (2) is accurate only under saturated conditions (i.e., each node always has a packet waiting for transmission), and far from accurate under unsaturated conditions if not filtered. Although the ARMA and Kalman Filters are very accurate, they are based on several strict assumptions, and too complex to implement in WSNs.

If degrading the requirements on timeliness, e.g., the player adjusts the strategy only one time in a game process, i.e., after transmitting a packet successfully or discarding a packet, a simplified game-theoretic MAC protocol - G-MAC is obtained.

In the active part, after transmitting a packet, to maintain the current contention level, the player adjusts CW_{min} as (4), where max(x, y) returns the larger value [13].

The parameter CW_{min}, CW_{max}, and CW at the right of (4) are the values of the nominal CW_{min}, CW_{max} and the final contention window used in the previous game process respectively. The parameter CW_{min} at the left of (4) is used in the current game process to transmit a new packet.

In CSMA/CA, a node starts a contention process always with the nominal CW_{min}, e.g., in IEEE 802.11b CW_{min}=32. So CSMA/CA has one main drawback: in a high load network the increase of the value of CW is obtained at the cost of continuous collision.

In G-MAC, after transmitting a packet, no matter it is transmitted successfully or not, the player does not start the next game process with the nominal CW_{min}. Given that the previous packet is transmitted successfully, the final value of CW is the optimal one. The best strategy for the player is to set CW_{min}=CW/2, to make use of the channel effectively. On the contrary, given that the previous packet is discarded, the best strategy for the player is to set CW_{min}=CW_{max}, to decrease collisions.

Obviously, compared with the game, the most attractive feature of G-MAC is that it is simple to implement. Firstly, no estimation mechanism is needed. Secondly, it is not needed to compute the optimal value of CW_{min}. That is to say, G-MAC would not cause any more energy consumption.

V. SIMULATION RESULTS

To evaluate DCF, S-MAC, the incompletely cooperative game and G-MAC, the following simulations are made in an ideal channel with none hidden terminals. The values of the parameters used to obtain numerical results for simulations are specified in IEEE 802.11 protocol. The channel rate is fixed at 1 Mb/s. Assume there are 30 nodes and each node generates new packets under a Poisson process. 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 in saturation conditions. The packets will be discarded only due to the re-transmission time reaches the retry limit, and do not consider the delay limit.

DCF is considered as the worst case: it has no energy saving features at all. The radio of each node does not go into the sleep mode. It is either in the listening/receiving mode or transmitting mode. S-MAC is considered as the basic contention-based protocol in WSNs. It includes the periodic active and sleeping time to achieve energy savings. The active and listening time for each player can be changed to different values. For simplicity, they are fixed at 250ms in the following simulations. In the game, besides the periodic active/sleeping time, in each active timeslot, assume each player can estimate the game state (i.e., the number of competing nodes) accurately, and then the player tunes its contention parameter CW_{min}. In G-MAC, each player tunes its local CW_{min} only one time at the end of each game process during the active time.

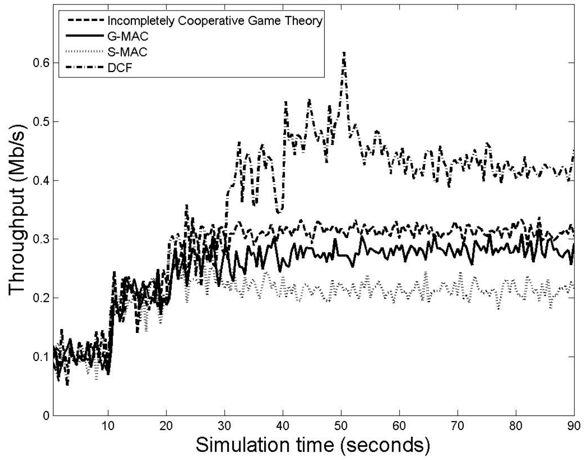

Figure 3. System throughput

Fig. 3 shows that the unsaturated throughput of DCF, S-MAC, the game and G-MAC become higher as the load increases and they have almost the same unsaturated throughput. Then S-MAC gets saturated and its throughput keeps almost constant, while the throughput of the game, G-MAC and DCF continue increasing as they are still unsaturated. And then G-MAC, the game and DCF get saturated in turn with the increasing load. After saturation, with the increasing of the load, the performance of DCF gets unstable, e.g., the throughput of DCF decreases.

As in the game and G-MAC each player can adapt to the variable game state and choose the corresponding equilibrium strategy, their capacity is higher than that of S-MAC. After saturation, their throughput almost keeps constant.

Fig. 4 shows that delay in G-MAC is a little lower than that in S-MAC especially under saturated conditions. In S-MAC each node gets the optimal *CW* after several collisions when transmitting every packet. In G-MAC the player gets the optimal *CW* after transmitting a packet successfully and it will reserve the value for the next transmission. If two nodes transmit at the same time and interfere with each other's transmission, packets are corrupted. Hence, the energy used during transmission and reception is wasted. In addition, the corrupted packets have to be re-transmitted, which increases energy consumption and latency. Hence, compared with S-MAC, G-MAC decreases delay by decreasing the collision probability. As a simplified incompletely cooperative game-theoretic MAC protocol, the delay in G-MAC is larger than that in the game.

Delay in DCF is much lower than that in the other three protocols under unsaturated conditions, which is due to the periodic sleeping state. However, after saturation, delay in DCF increases sharply.

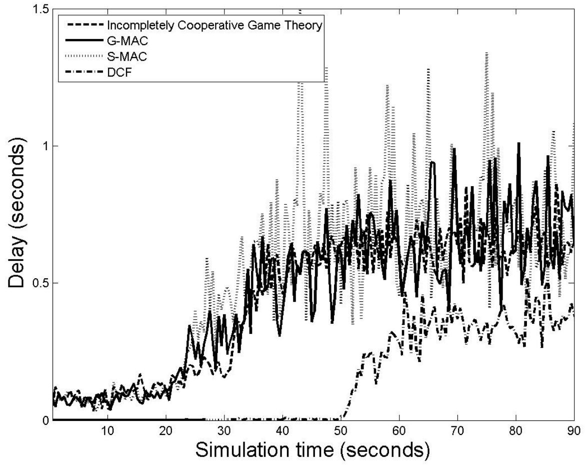

Figure 4. Access delay

Fig. 5 shows that packet-loss-rate in the four protocols increases with the load, and that in S-MAC increases most sharply after the system is saturated. The saturated packet-loss-rate in S-MAC and DCF is about from 2% to 4%, while the former is a litter higher than the latter, and that in G-MAC and the game is almost zero, which is due to incompletely cooperative game theory. Please note that packet-loss-rate in G-MAC may occasionally be large as the player can not adjust its strategy to the variable game state as timely as it does in the game.

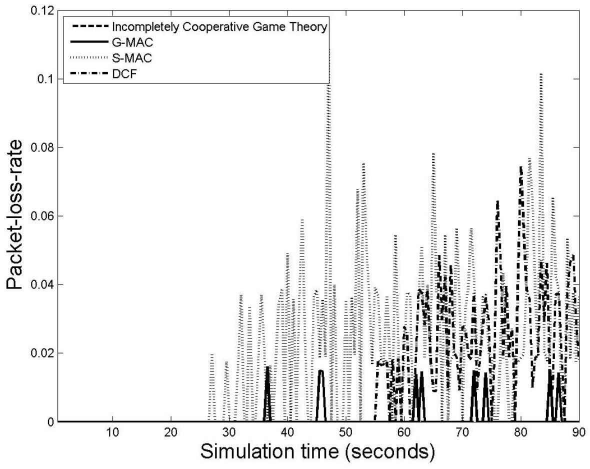

Figure 5. Packet-loss-rate

Fig. 6 shows that S-MAC, the game and G-MAC have almost the same energy consumption. As the active time is fixed as the same as the sleeping time, energy consumption in the three protocols is almost twice than that in DCF.

Fig. 7 shows that energy efficiency (i.e., the ratio of the successfully transmitted bit rate to energy consumption) in the game is higher than that in G-MAC, and much higher than that in S-MAC and DCF. Although throughput of DCF is much higher than that of the other three protocols, as its energy consumption is the largest too, its energy efficiency is the lowest.

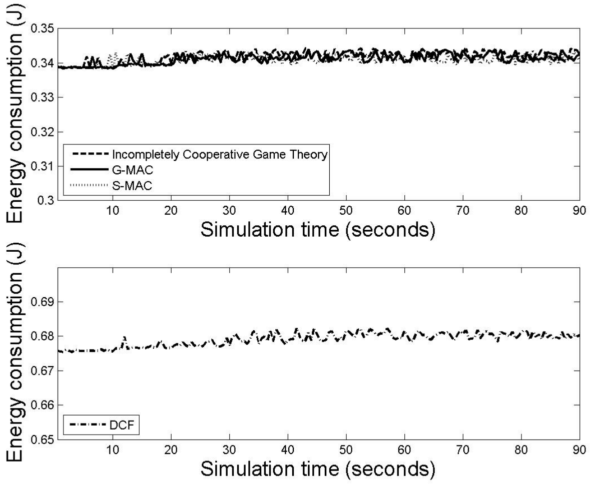

Figure 6. Energy consumption

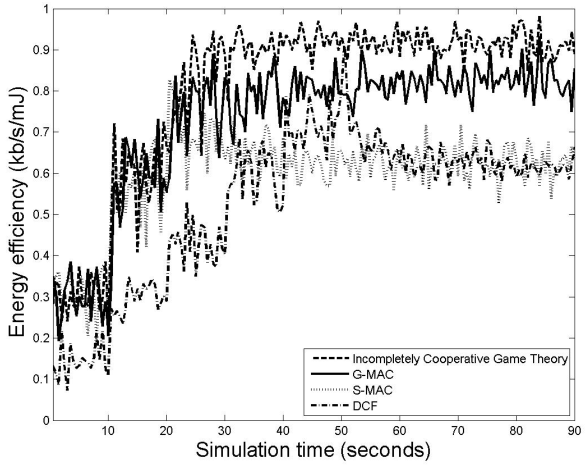

Figure 7. Energy efficiency

Moreover, Fig. 6-7 shows that in order to evaluate an energy-aware protocol, both energy consumption and energy efficiency should be considered simultaneously.

VI. CONCLUSION

In this paper, incompletely cooperative game theory is used improve the system performance of WSNs. In this game, firstly, each player estimates the game state; secondly, the player adjusts its equilibrium strategy to the estimated game state by tuning its local contention parameters. Analysis results show that when using the game in WSNs, the key problem is how to design a suitable equilibrium strategy based on the conditional game. Moreover, a simplified G-MAC protocol based the incompletely cooperative game is presented, which is easy to implement in current WSNs. Simulation results show that the incompletely cooperative game is an appropriate tool to improve throughput, and decrease delay and packet-loss-rate, while increasing energy efficiency.

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