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Game-theoretic medium access control protocol for wireless sensor networks

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Abstract: In the traditional medium access control (MAC) protocols for wireless sensor networks (WSNs), energy consumption is traded for throughput and delay. However, in future WSNs, throughput and delay performance had better not be sacrificed for energy conservation. Here first, an incompletely cooperative game-theoretic heuristic-based constraint optimisation framework is introduced to achieve the goals of throughput, delay and energy conservation simultaneously. Then a simplified game-theoretic MAC (G-MAC) protocol is presented, which can be easily implemented in WSNs. Simulation results show that compared with two typical MAC protocols for WSNs, sensor MAC and timeout MAC, G-MAC can increase system throughput, and decrease delay and packet-loss-rate, while maintaining relatively low energy consumption.

1 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 optimisation of WSNs, especially medium access control (MAC) protocols, have attracted much research interests. Traditional MAC protocols for wireless *ad hoc* networks are designed to maximise throughput and minimise 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 efficiency [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 design for WSNs can be broadly divided into scheduling-based [2], collision-free [3], contention-based [4–8] and hybrid schemes [9]. Scheduling-based protocols, for example, time division multiple access (TDMA), have a natural advantage of energy conservation compared with contention-based protocols, because the duty cycle of the radio is reduced and there is no contention-introduced overhead and collision. However, maintaining a TDMA schedule (e.g. time synchronisation) in WSNs is not an easy task and will result in complexity in the sensor nodes. Contention-free protocols can decrease energy consumption by decreasing collision and have the potential to increase throughput and decrease delay. However, current contention-free protocols require multiple independent wireless channels or radios, and are too complex to be implemented in the sensor nodes. Zebra MAC (Z-MAC), a typical hybrid protocol, can combine the strengths of TDMA and carrier sense multiple access (CSMA) [9]. However, current hybrid protocols still have to further offset the weakness of incorporated protocols.

Currently, IEEE 802.11 distributed coordination function (DCF), one of typical contention-based protocols, has been the de facto MAC standard for wireless *ad hoc* networks, widely used in almost all of the testbeds. DCF is based on CSMA with collision avoidance (CSMA/CA) and a binary exponential backoff mechanism. Before transmitting, a node generates a random backoff interval. The backoff time is slotted and the number of the backoff slots 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 CW. After each unsuccessful transmission, CW is doubled up to the maximum value CW_{max}. Once CW reaches CW_{max}, it will remain at the value until the packet is transmitted successfully or

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discarded. If the packet is retransmitted more than a certain time called retry limit, retransmission attempts will cease and the packet will be discarded. Since a node does not know when it will be receiving a packet from one of its neighbours, 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, which is mainly called problem of idle listening [10].

CSMA/CA-based sensor MAC (S-MAC) is explicitly designed for WSNs to solve this problem. In S-MAC, each node periodically sleeps, wakes up, listens to the channel and then returns to sleep [4]. During the sleeping period, the node turns-off its radio to preserve energy. During the active period, it can communicate with its neighbours and send the messages queued during the sleeping period. Throughput is reduced because only the active period is used for communication. Delay increases because a message-generating event may occur during the sleeping period. In that case, the message will be queued until the start of the next active period.

To handle load variations in time and location, timeout MAC (T-MAC) dynamically ends the active period [5]. At the beginning of each active period, there is a very short listening window to send or receive the RTS and CTS frames. If no activity occurs in that period, the node returns to sleep. Moreover, during the active period, if a node has no data to transmit or receive for a certain time, it will enter into the sleeping mode immediately. Wireless sensor MAC (WiseMAC) is an iteration on Aloha with preamble sampling specifically designed for infrastructure WSNs [6]. WiseMAC provides a lower power consumption for the same delay than the power management protocol used in the IEEE 802.15.4 ZigBee standard. To achieve a low-power operation, Berkeley MAC (B-MAC) employs an adaptive preamble sampling scheme to reduce duty cycle and minimise idle listening [7]. B-MAC supports on-the-fly reconfiguration and provides bi-directional interfaces for system services to optimise performance. Dynamic S-MAC (DSMAC) dynamically changes the sleeping interval with fixed listening interval length and therefore the duty cycle of sensors is adjusted to adapt to the current traffic condition [8]. Moreover, DSMAC only introduces insignificant overhead than S-MAC.

In a word, the basic idea of these contention-based MAC protocols is to trade throughput and delay for energy consumption. However, there is an increasing demand for WSNs to support real-time traffic, which have certain requirements on throughput and delay. So the future WSNs should achieve all the goals, energy consumption, throughput and delay at the same time, and could not only use the above simple idea. In this paper, a game-theoretic MAC (G-MAC) protocol is proposed, which is based on a novel concept of incompletely cooperative game theory used in mobile *ad hoc* networks [11]. As the proposed MAC protocol in [11] is designed to maximise throughput and minimise delay without any energy constraint, it is modelled as game-theoretic unconstraint optimisation. In this paper, the problem of MAC protocols in WSNs is modelled as an incompletely cooperative game-based constraint optimisation, and its equilibrium strategy is re-designed in the context of WSNs. The novel model provides a heuristic approach to improve the performance of MAC protocols. Another important contribution of this paper is to provide G-MAC, a simplified G-MAC protocol, based on the model. Simulation results show that G-MAC supports the incompletely cooperative game effectively in WSNs, for example, increasing throughput and decreasing delay with limited energy consumption.

The rest of this paper is organised as follows. In Section 2, after discussing the equilibrium strategy of the incompletely cooperative game-based constraint optimisation, a heuristic approach is provided to achieve the global optima. In Section 3, a simplified G-MAC protocol is presented, which is easy to be implemented in WSNs, although it is a sub-optimal mechanism. In Section 4, simulation studies are carried out to evaluate the performance of G-MAC. The concluding remarks are given in Section 5.

2 Incompletely cooperative game-based constraint optimisation

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 recognising stable outcomes [12]. Games may generally be categorised 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 its own interests. Unlike in non-cooperative games, in cooperative games, the players can make binding commitments. Recently, game theory is widely used to analyse and improve the performance of wireless *ad hoc* networks [13] and WSNs [14–19], for example, routing protocols [16] and power management mechanisms [14, 18]. Xiao *et al.* [13] proposed a simple game model to interpret DCF and a simple Nash equilibrium backoff strategy to resolve the unfairness problem. However, to do so each node has to broadcast its local signal-to-noise ratio periodically to its neighbours. When using game theory in WSNs rather than mathematics or economics, much attention should be paid to the relevant context of WSNs. For example, explicit cooperation among nodes is clearly impossible in WSNs. Enrique *et al.* [14] proposed a distributed scheme for efficient power management in WSNs, which is based upon a game-theoretic mathematical structure that induces a natural mapping between the information layer and the physical layer. And sufficient conditions are provided for the convergence of the algorithm to a pure Nash equilibrium. However, based on non-cooperative game theory, the algorithm is guaranteed to identify sub-optimal topologies in an online fashion. On the basis of the proposed queuing model, Niyato *et al.* [19]

formulated a bargaining game by exploiting the trade-off between packet blocking and packet dropping probabilities due to the sleep and wakeup dynamics in WSNs. The Nash solution is obtained for the equilibrium point of sleep and wakeup probabilities. However, Niyato *et al.* [19] assume that a sensor node can receive and transmit packets in non-overlapping time slots as in a TDMA-based wireless access system. As discussed above, it is difficult to maintain a TDMA schedule in WSNs. Moreover, only two performance measures (i.e. packet blocking and packet dropping probabilities) are considered in the game. Hence, in this paper, a novel concept of incompletely cooperative game theory is introduced into WSNs. The basic idea of the proposed game is that each node adjusts its equilibrium strategy to the estimated game state without explicit cooperation among nodes [11].

In the proposed game, a player starts a game process when a new packet arrives at its transmission buffer and ends when the packet is moved out of the buffer (i.e. transmitted successfully or discarded). When the player transmits the next packet, the game state could be changed by the player or the other nodes. So the incompletely cooperative game is considered as a finitely repeated game, and restarted from the beginning upon the new arrival of a packet. Each game process includes many time slots and each time slot corresponds to one game state. In each time slot, each player (i.e. node) estimates the current game state based on its history. After estimating the game state, the player adjusts its own equilibrium strategy by tuning its local contention parameters. Then all the nodes take actions simultaneously, that is, transmitting, listening or sleeping. Although the player does not know which action the other nodes (i.e. its opponents) are taking now, it can predict its opponents' actions according to its own history.

In the context of WSNs, it is impossible for the nodes to exchange the game state periodically, which causes additional energy and bandwidth consumption. However, as each node keeps sensing the channel to receive possible packets to itself in the active period, it can estimate the game state by listening to the channel. So in the game, each node takes a distributed approach of detecting and estimating the current game state, and tuning its local contention parameters to the estimated game state. Moreover, in economics, normally, the optimal target of the player is to maximum its own profits. However, in WSNs, the target of each node is to maximise the system performance under certain constraints, for example, energy consumption. So an incompletely cooperative game-based constraint optimisation is presented for WSNs.

In the game, the utility function of a player (e.g. node i), $\mu_i = \mu_i(s_i, \bar{s}_i)$. The strategy of the player, s_i, includes three possible actions: transmitting, listening or sleeping if not considering the other nodes. The strategy profile of its opponents (i.e. all the other $n-1$ neighbours), $\bar{s}_i = (s_1, s_2, \ldots, s_{i-1}, s_{i+1}, \ldots, s_n)$. Similarly, the utility function of the opponents, $\bar{\mu}_i = \bar{\mu}_i(\bar{s}_i, s_i)$. 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 if a player is a node contending for the channel. Hence, in the game, a player is not always a node. If we analyse the equilibrium strategy of the node i, Player 1 is the node i, and Player 2 is all the other $n-1$ nodes. In fact, it is possible for Player 1 to estimate Player 2's state, and difficult to estimate the states of each node in Player 2. Then the optimal strategy of the two players are obtained as

$$\begin{aligned} s_i^* &= \arg\max_{s_i} \bar{\mu}_i(\bar{s}_i, s_i)|(e_i < e_i^*) \\ \bar{s}_i^* &= \arg\max_{\bar{s}_i} \mu_i(s_i, \bar{s}_i)|(\bar{e}_i < \bar{e}_i^*) \end{aligned} \tag{1}$$

where e_i, e_i^*, $\bar{e}_i$ and $\bar{e}_i^*$ are the energy consumption and the energy limit of Player 1 and Player 2, respectively.

Obviously, Player 1 adjusts its strategy s_i not to obtain its own optimal utility, but to help Player 2 obtain the optimal utility, and vice versa. Hence, it indicates that all the nodes play the cooperative game based on the estimated game states. On the other hand, the two players obtain the optimal utility under the energy constraint. It indicates that all the nodes play the constraint game.

Table 1 is the strategy table with two players (i.e. n nodes), which could be traced back to a famous game paradigm, the Prisoners' Dilemma [25]. As Player 2 includes $n-1$ nodes, the transmission may be collided among the $n-1$ nodes. So Player 2 includes four possible actions: successful transmission,

Table 1 Incompletely cooperative game model for WSNs

		Player 2/Opponents (all the other $n-1$ nodes)			
		Successful transmission $(1-\bar{w}_i)\bar{\tau}_i(1-\bar{p}_i)$	Failed transmission $(1-\bar{w}_i)\bar{\tau}_i\bar{p}_i$	Listening $(1-\bar{w}_i)(1-\bar{\tau}_i)$	Sleeping $\bar{w}_i$
player 1 (node i)	transmitting $(1-w_i)\tau_i$	$(c_f, \bar{c}_f)$		$(c_s, \bar{c}_i)$	$(c_f, \bar{c}_w)$
	listening $(1-w_i)(1-\tau_i)$	$(c_i, \bar{c}_s)$	$(c_i, \bar{c}_f)$	$(c_i, \bar{c}_i)$	$(c_i, \bar{c}_w)$
	sleeping w_i	$(c_w, \bar{c}_f)$		$(c_w, \bar{c}_i)$	$(c_w, \bar{c}_w)$

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failed transmission, listening or sleeping if not considering Player 1. With regard to the payoff of Player 2 in a given time slot, there are four possibilities. First, Player 2 sleeps with the probability of $\bar{w}_i$, whose payoff is $\bar{c}_w$. Second, Player 2 listens to the channel with the probability of $(1-\bar{w}_i)(1-\bar{\tau}_i)$, whose payoff is $\bar{c}_i$. Third, Player 2 fails to transmit packets due to the collisions between the two players or among the $n-1$ nodes within Player 2 with the probability of $(1-\bar{w}_i)\bar{\tau}_i((1-w_i)\tau_i+\bar{p}_i(1-w_i)(1-\tau_i)+w_i)$, whose payoff is $\bar{c}_f$. Finally, Player 2 transmits successfully with the probability of $(1-\bar{w}_i)\bar{\tau}_i(1-\bar{p}_i)(1-w_i)(1-\tau_i)$, whose payoff is $\bar{c}_s$. Here, τ_i and $\bar{\tau}_i$ are the conditional transmission probabilities of the two players, respectively, and $\bar{p}_i$ is the conditional collision probability of Player 2. With regard to the payoff of Player 1 in a given time slot, there are four possibilities too. First, Player 1 sleeps with the probability of w_i, whose payoff is c_w. Second, Player 1 listens to the channel with the probability of $(1-w_i)(1-\tau_i)$, whose payoff is c_i. Third, Player 1 fails to transmit its packets due to the collision between the two players with the probability of $\tau_i(1-w_i)((1-\bar{w}_i)\bar{\tau}_i+\bar{w}_i)$, whose payoff is c_f. Finally, Player 1 transmits successfully with the probability of $(1-w_i)\tau_i(1-\bar{w}_i)(1-\bar{\tau}_i)$, whose payoff is c_s. Hence, the optimal strategies of the two players under the given constraints are expressed as

$$\begin{aligned}s_i^* &= \underset{(w_i,\tau_i)}{\arg\max}((1-\bar{w}_i)((1-\bar{\tau}_i)\bar{c}_i+\bar{\tau}_i(1-\bar{p}_i)(1-w_i)\\ &\quad\times(1-\tau_i)\bar{c}_s+\bar{\tau}_i((1-w_i)\tau_i+\bar{p}_i(1-w_i)(1-\tau_i)+w_i)\bar{c}_f)\\ &\quad+\bar{w}_i\bar{c}_w)|(e_i<e_i^*)\\ \bar{s}_i^* &= \underset{(\bar{w}_i,\bar{\tau}_i)}{\arg\max}((1-w_i)(\tau_i(1-\bar{w}_i)(1-\bar{\tau}_i)c_s+(1-\tau_i)c_i\\ &\quad+\tau_i((1-\bar{w}_i)\bar{\tau}_i+\bar{w}_i)c_f)+w_ic_w)|(\bar{e}_i<\bar{e}_i^*).\end{aligned} \tag{2}$$

where $\bar{p}_i$ is the function of $\bar{\tau}_i$, that is, $\bar{p}_i = 1-(1-\bar{\tau}_i)^{n-2}$ [11].

In general, the contention-based MAC protocol in WSNs is modelled as a game-theoretic constraint optimisation problem, which provides a heuristic approach to improve the performance of MAC protocols. On the basis of the estimated game state, each node achieves the global optima by adjusting its sleeping and conditional transmission probability simultaneously.

However, unfortunately, the above problem has been proven to be NP-hard [20], so we cannot hope an algorithm that can find the theoretical optimum and runs in polynomial time. Hence, we present a simplified G-MAC protocol for WSNs.

3 G-MAC protocol for WSNs

In G-MAC time is divided into super-frames. Every super-frame has two parts: an active part and a sleeping part. During the active part, if a node has packets to send, it will contend for the channel in the incompletely cooperative game mode. During the sleeping part, every node turns-off its radio to preserve energy. The time length of the active and sleeping part is adjusted according to the estimated game state too.

Several performance evaluation studies show that the performance of CSMA/CA is very sensitive to the number of competing nodes, that is, the number of nodes that are simultaneously trying to send a packet on the shared medium [21]. For simplicity, in this paper, the game state is the number of competing nodes. This information cannot be retrieved from CSMA/CA operation. Research results [11] show that the number n of competing nodes is the function of the conditional collision probability (p) and transmission probability (τ) of the node, as follows

$$p = 1-(1-\tau)^{n-1} \Rightarrow n = 1+\frac{\log(1-p)}{\log(1-\tau)} \tag{3}$$

Since the probability τ and p can be independently measured by each node by simply monitoring the channel activity (actually all the nodes always listen to the channel during the active part), it follows that each node can estimate the value n.

However, Vercauteren *et al.* [22] show that (3) 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. Bianchi and Tinnirello [23] provide two perfect run-time estimation mechanisms, that is, auto regressive moving average and Kalman filters. However, they are too complex to be implemented in WSN nodes. We present the concept of incompletely cooperative game theory, but do not provide any run-time estimation algorithm in [11]. In [24] we provide a simple estimation mechanism, that is virtual CSMA/CA (V-CSMA/CA). If a node has no packets to send, it will contend for the channel to transmit a virtual packet. When V-CSMA/CA decides to send a virtual frame, unlike the case of real frames, no frame is transmitted. V-CSMA/CA would estimate the probability of collision as if a virtual frame was really sent. After transmitting the virtual frame, the node detects the channel immediately at the next time slot. If the channel is idle (i.e. no other nodes transmit real frames in the slot), the node assumes that its virtual frame has been transmitted successfully. Otherwise, if any other node transmits in the time slot and the channel is busy, the node assumes that its virtual frame is collided. As no real frames are transmitted in V-CSMA/CA, it would not affect the contention of other nodes. Now the node can estimate the number n by using (3) as it always has packets to send (i.e. real or virtual one).

In G-MAC, after estimating the game state, each player adjusts its strategy by tuning contention parameters, such as $\mathrm{CW}_{\min}$ [11], as follows

$$\mathrm{CW}_{\min} = \mathrm{floor}(n \times \mathrm{rand}(7, 8)) \tag{4}$$

where rand (x, y) returns a random value between x and y. Research results show that the optimal value of $\mathrm{CW}_{\min}$ is dependent on the number n, and the ratio of the optimal $\mathrm{CW}_{\min}$ to n is about from 7 to 8 [26].

According to (2), to obtain the global optima, each node should adjust not only its conditional transmission probability but also its sleeping probability to the estimate game state. However, up to now, the optimal equilibrium point of the time length of the active and sleeping part (i.e. the sleeping probability) has not been obtained. So in G-MAC, the node changes the length of the active part (T_{active}) and the sleeping part (T_{sleep}), in a simplified method (as shown at the bottom of the page)

where $\max(x, y)$ and $\min(x, y)$ return the larger and smaller value, respectively. The parameter $T_{\text{active}}^{\text{current}}$ and $T_{\text{sleep}}^{\text{current}}$ at the right hand are the values of the length of the active and sleeping part, respectively, in the current time slot. The parameter $T_{\text{active}}^{\text{next}}$ and $T_{\text{sleep}}^{\text{next}}$ at the left hand are used in the next time slot. The parameter $T_{\text{active,max}}$, $T_{\text{active,min}}$, $T_{\text{sleep,max}}$ and $T_{\text{sleep,min}}$ are the maximum and minimum length of the active and sleep part. The parameter α and β are two predetermined integers. The parameter δt is a predetermined time interval.

Fig. 1 shows the basic scheme of (5). If the estimated number of competing nodes is larger than the predetermined upper limit α, it indicates many nodes still have packets to send. So the length of the active part is increased by δt but not longer than the maximum length of the active part. Simultaneously, the length of the sleep part is decreased by δt so that the length of the super-frame keeps constant. On the other hand, if the estimate number of competing nodes is smaller than the predetermined low limit β, the length of the next active part is decreased by δt but not shorter than the minimum length of the active part. Simultaneously, the length of the sleep part is increased by δt.

4 Simulation results

To evaluate DCF, S-MAC, T-MAC and G-MAC, the following simulations are made with OPNET in an ideal channel. The values of the parameters used to obtain numerical results for simulations are specified in IEEE 802.11x. The channel rate is fixed at 1 Mb/s. Suppose that there are 50 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 the saturation condition.

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 sleeping mode. It is either in the listening/receiving mode or transmitting mode. S-MAC is considered as the basic contention-based MAC protocol in WSNs. It includes the periodic active and sleeping time to achieve energy savings. For simplicity, the active and listening time are fixed at 250 ms in the following simulations. T-MAC is considered as the basic adaptive MAC protocol in WSNs. In G-MAC, besides the periodic active/sleeping time, in the active time slot, each node adjusts its sleeping and conditional transmission probability adaptively to the estimated game state.

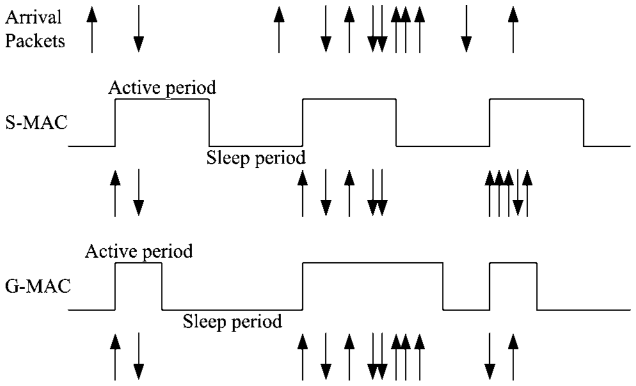

Figure 1 *Super-frame format*

Fig. 2 shows that the four protocols have almost the same unsaturated throughput, and the saturated throughput of DCF is the highest as there is no sleeping period. Since the active and sleeping time are fixed at the same value, the saturated throughput of S-MAC is about 50% of that in DCF. Unlike S-MAC, the active time of T-MAC can be adjusted according to the network load. In T-MAC, nodes increase the time length of the active part under the high-network load, so its throughput is about 30% larger than that of S-MAC under the high-network load. In G-MAC, nodes can adapt to the variable game state and choose the corresponding equilibrium strategy to decrease collisions, so its saturated throughput is about 10% higher than that of T-MAC.

Fig. 3 shows that the average delay in G-MAC is lower than that in S-MAC and T-MAC as there are more collisions in S-MAC and T-MAC. In T-MAC, nodes decrease the time length of the active part under the low-network load, so its delay is larger than that of S-MAC under the low-network load. On the contrary, the delay in T-MAC is lower than that of S-MAC under the high-network load. In S-MAC and T-MAC, each node obtains the optimal CW after several collisions and in G-MAC after estimating the game state. Hence,

$$\begin{cases} T_{\text{active}}^{\text{next}} = \max\left(T_{\text{active}}^{\text{current}} + \delta t,\ T_{\text{active, max}}\right) & T_{\text{sleep}}^{\text{next}} = \min\left(T_{\text{sleep}}^{\text{current}} - \delta t,\ T_{\text{sleep, min}}\right) \quad \hat{n} \geq \alpha \\ T_{\text{active}}^{\text{next}} = \min\left(T_{\text{active}}^{\text{current}} - \delta t,\ T_{\text{active,min}}\right) & T_{\text{sleep}}^{\text{next}} = \max\left(T_{\text{sleep}}^{\text{current}} + \delta t,\ T_{\text{sleep, max}}\right) \quad \hat{n} \leq \beta \\ T_{\text{active}}^{\text{next}} = T_{\text{active}}^{\text{current}} & T_{\text{sleep}}^{\text{next}} = T_{\text{sleep}}^{\text{current}} \quad \text{else} \end{cases} \tag{5}$$

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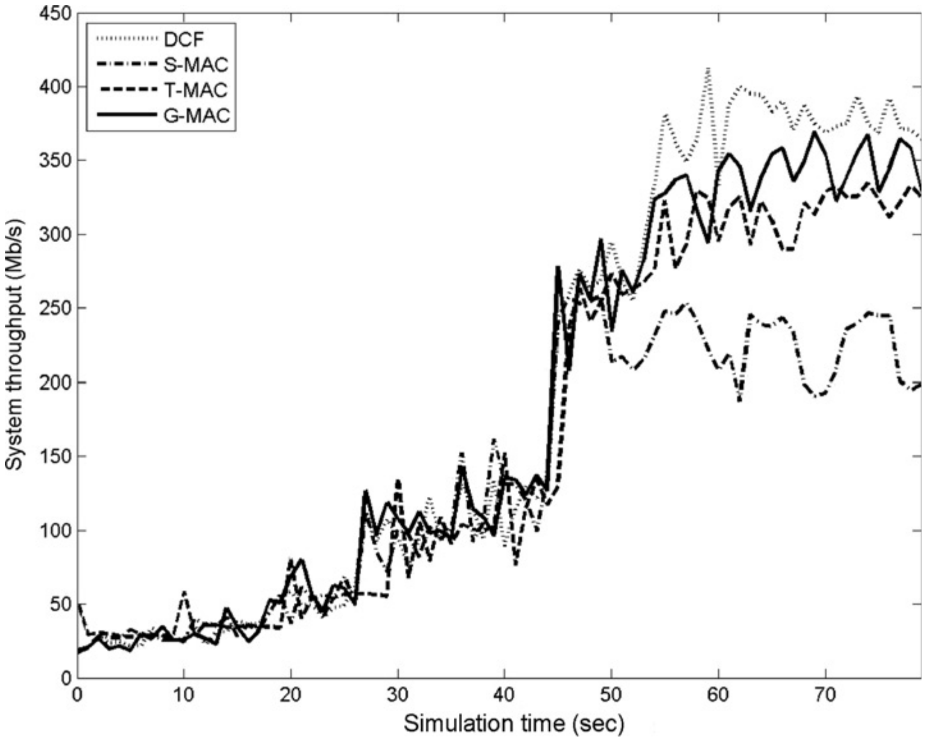

Figure 2 *System throughput*

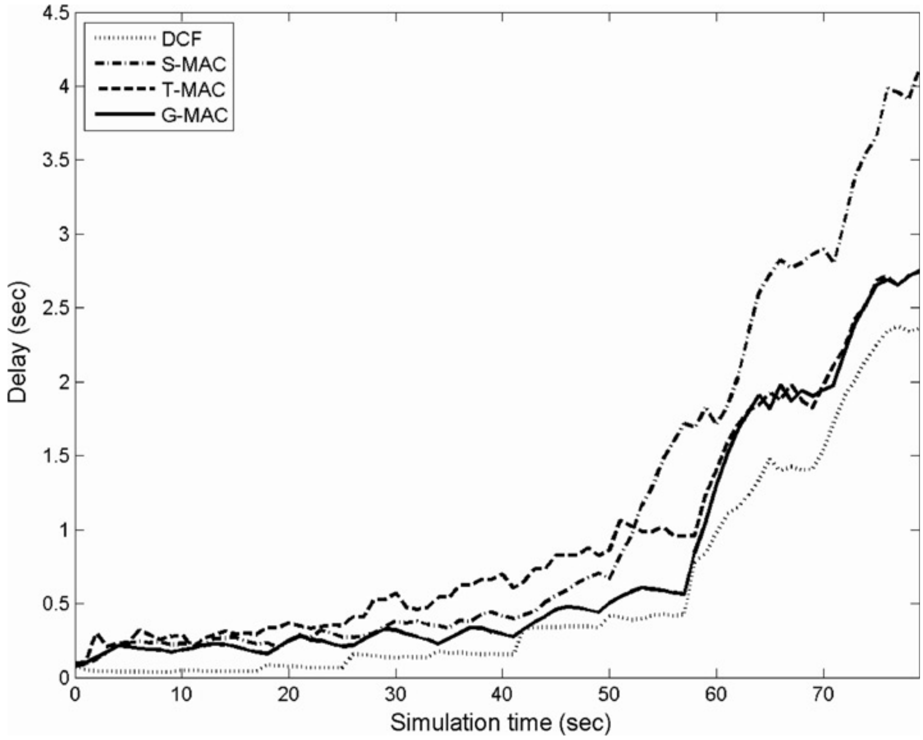

Figure 3 *Delay*

compared with S-MAC and T-MAC, G-MAC decreases the following two delays by decreasing collisions. First, backoff delay happens when carrier sense failed because collision occurs. Second, retransmission delay happens when the packet is collided and has to be retransmitted. So the delay in G-MAC is always lower than that in S-MAC under different network loads. Delay in DCF is lower than that in S-MAC, T-MAC and G-MAC, which is due to the periodic sleeping state in the latter three protocols.

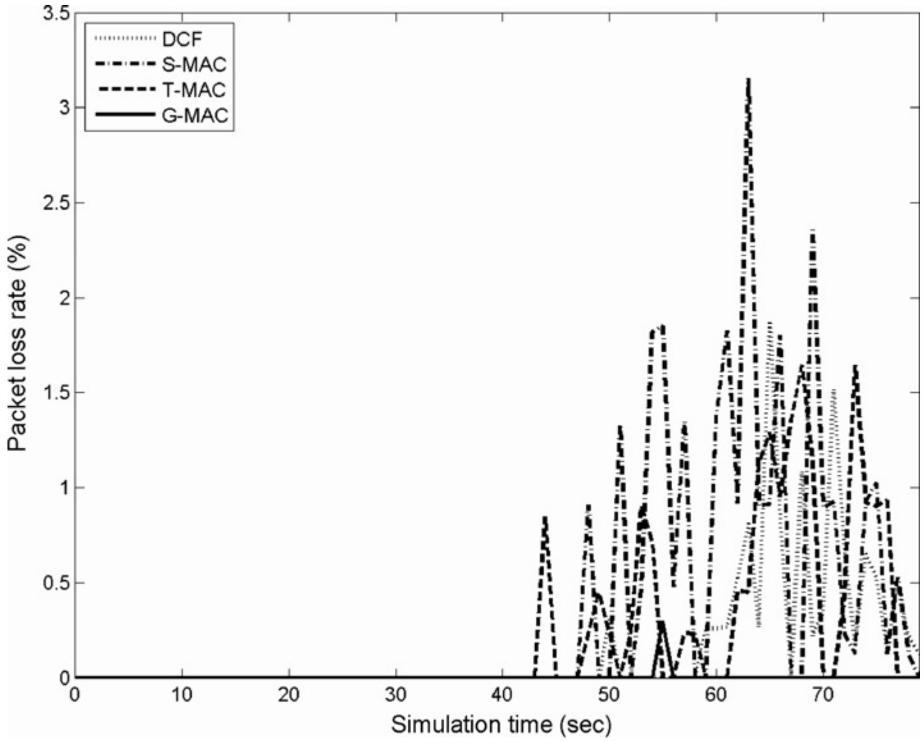

Figure 4 *Packet-loss-rate*

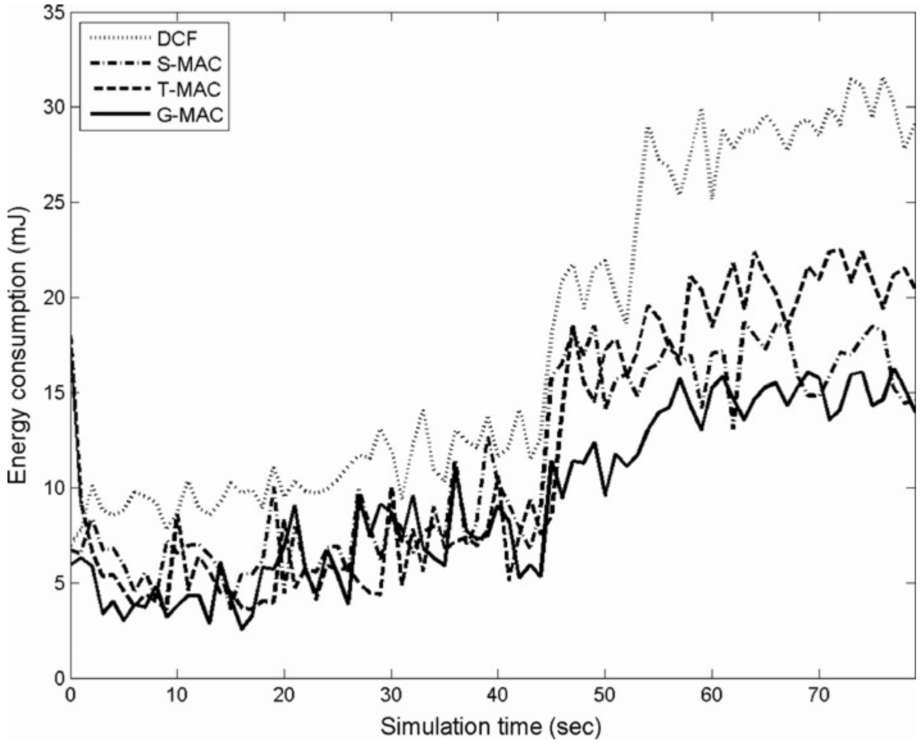

Figure 5 *Energy consumption*

Fig. 4 shows that packet-loss-rate in S-MAC increases most sharply, followed by that in DCF and T-MAC, after the system is saturated. The saturated packet-loss-rate in S-MAC is higher than that of T-MAC and DCF, and that in G-MAC is almost zero, which is due to the incompletely cooperative game. In G-MAC, each node can adjust its strategy to the current game state, and transmit its packets successfully before the retransmission time reaches the retry limit.

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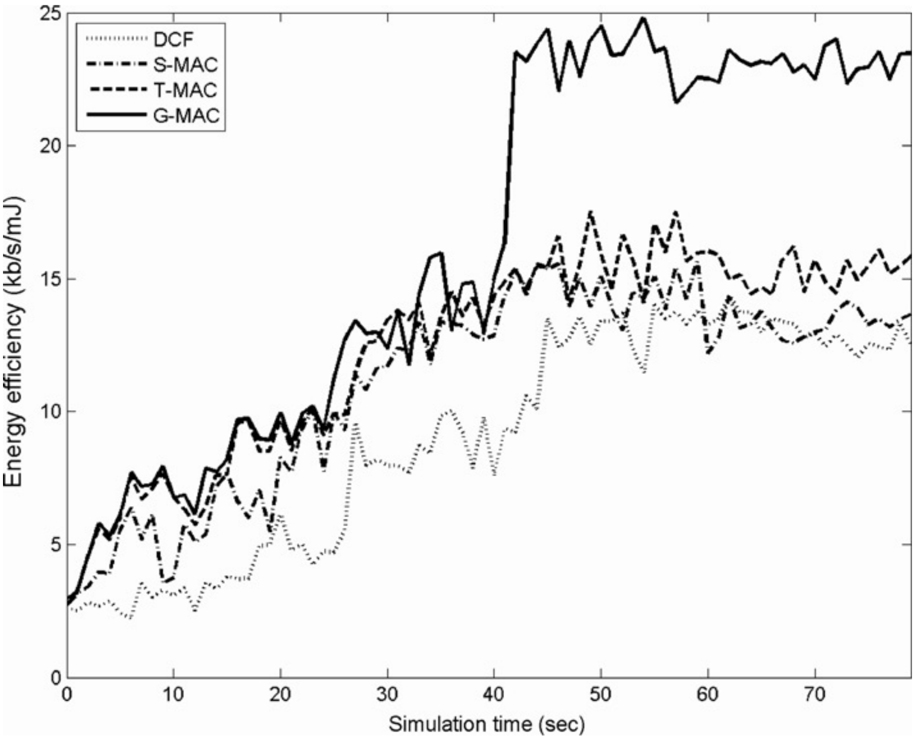

Figure 6 *Energy efficiency*

Moreover, Fig. 3 shows that under the saturation condition, G-MAC and T-MAC have almost the same delay; however, in T-MAC more packets are discarded, as shown in Fig. 4.

Fig. 5 shows that the total energy consumption in G-MAC and S-MAC is about 50% of that in DCF, which is due to the periodic sleeping in the two protocols. If two nodes transmit at the same time slot 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 retransmitted, which increases energy consumption, bandwidth overhead, and latency. As G-MAC decreases collision, its energy consumption is lower than that in S-MAC and T-MAC.

As an energy-aware MAC protocol, G-MAC considers not only energy consumption but also energy efficiency (i.e. the ratio of the successfully transmitted bit rate to energy consumption). On the basis of the incompletely cooperative game, G-MAC can maximise its throughput under the energy limit. So its energy efficiency in G-MAC is about 50% higher than that in S-MAC, T-MAC and DCF, as shown in Fig. 6, although the throughput in DCF is higher than that in G-MAC, as shown in Fig. 2. Energy efficiency in T-MAC is higher than that in S-MAC as T-MAC decreases the energy consumption by reducing idle listening time. Energy efficiency in S-MAC is higher than that in DCF before saturation, while after saturation, S-MAC and DCF have almost the same energy efficiency. It indicates that S-MAC only considers how to decrease its used energy, and not to increase its throughput.

5 Conclusion

In this paper, the problem of the energy-efficient MAC protocols for WSNs is modelled as an incompletely cooperative game-based constraint optimisation. On the one hand, all the nodes play the cooperative game based on the estimated game states. On the other hand, the nodes obtain the optimal utility under the energy constraint. And a new equilibrium strategy is presented for the model, which provides a heuristic approach to improve the performance of MAC protocols. Then a simplified MAC protocol (G-MAC) is provided in this paper, which can be easily implemented in WSN nodes. In G-MAC, an active/sleep duty cycle is introduced to reduce energy consumption. During the active period, first, each node estimates the current game state (e.g. the number of competing nodes). Second, the node adjusts its local contention parameters (e.g. the minimum CW) and the time length of the active and sleeping part to the estimated game state separately. Compared with DCF, G-MAC can decrease 50% of energy consumption. Compared with S-MAC, G-MAC can improve throughput and decrease delay and packet-loss-rate, for example, 40% system throughput increase. Compared with T-MAC, G-MAC can increase up to 30% in energy efficiency. In general, G-MAC can achieve a much better performance with the same energy consumption as S-MAC or T-MAC.

We are carrying out research in the following two topics. First, in this paper, we provide a simplified method to address the sleeping probability. We are developing an analytical model to obtain the optimal equilibrium of the sleeping probability, and to guarantee the convergence of (5). Second, according to (2), in order to achieve the global optima, we should adjust the conditional transmission probability and sleeping probability jointly. However, in this paper, for simplicity, we have to adjust them separately. We shall present an algorithm to change the two parameters simultaneously.

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