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Research Article

An Energy-Efficient MAC Protocol in Wireless Sensor Networks: A Game Theoretic Approach

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Game Theory provides a mathematical tool for the analysis of interactions between the agents with conflicting interests, hence it is well suitable tool to model some problems in communication systems, especially, to wireless sensor networks (WSNs) where the prime goal is to minimize energy consumption than high throughput and low delay. In this paper, we use the concept of incomplete cooperative game theory to model an energy efficient MAC protocol for WSNs. This allows us to introduce improved backoff algorithm for energy efficient MAC protocol in WSNs. Finally, our research results show that the improved back off algorithm can improve the overall performance as well as achieve all the goals simultaneously for MAC protocol in WSNs.

1. Introduction

Communication in wireless sensor networks is divided into several layers. Medium Access Control (MAC) is one of those layers, which enables the successful operation of the network. MAC protocol tries to avoid collisions by not allowing two interfering nodes to transmit at the same time. The main design goal of a typical MAC protocols is to provide high throughput and QoS. On the other hand, wireless sensor MAC protocol gives higher priority to minimize energy consumption than QoS requirements. Energy gets wasted in traditional MAC layer protocols due to idle listening, collision, protocol overhead, and overhearing [1, 2]. There are some MAC protocols that have been especially developed for wireless sensor networks. Typical examples include S-MAC, T-MAC, and H-MAC [2–4]. To maximize the battery lifetime, sensor networks MAC protocols implement the variation of active/sleep mechanism. S-MAC and T-MAC protocols trades networks QoS for energy savings, while H-MAC protocol reduces the comparable amount of energy consumption along with maintaining good network QoS. However, their backoff algorithm is similar to that of the IEEE 802.11 Distributed Coordinated Function (DCF), which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Mechanism. The energy consumption using CSMA/CA is high when nodes are in backoff procedure and in idle mode. Moreover, a node that successfully transmits resets it Contention Window (CW) to a small, fixed minimum value of CW. Therefore, the node has to rediscover the correct CW, wasting channel capacity, and increase the access delay as well. So, during the CSMA/CA mechanism, backoff window size and the number of active nodes are the major factors to have impact on the network performance and over all energy efficiency of MAC protocol. Hence, it is necessary to estimate the number of nodes in network to optimize the CSMA/CA operation. Furthermore, optimizing CSMA/CA operation is more challenging task for self-organizing and distributed networks as there are no central nodes to assign channel access in sensor nodes.

In sensor networks, each node has a direct influence on its neighboring nodes while accessing the channel. So, these interactions between nodes and aforementioned observations lead us to use the concepts of game theory that could improve the energy efficiency as well as the delay performance of MAC protocol. More on this will be discussed in section two of this paper.

Recently lots of researchers have started using game theory as a tool to analyze the wireless networks. Their game

Table 1: A wirless networking game.

Components of a game	Elements of a wireless network
Players	Nodes in the wireless network
A set of actions	A modulation scheme, transmit power level, and so forth.
A set of preferences	Performance metrics (e.g., Energy Efficiency, Delay, etc.)

theoretic approaches were proposed to the wide area of wireless communication right from the security issues to power control, and so forth, [5–8]. To model WSNs problems into full information game theoretic problems is an extremely difficult task due to distributed nature of WSNs. In addition, full information sharing also results into additional energy and bandwidth consumption. So, we use the concept of incomplete cooperative game theory to solve the aforementioned challenges. In this paper, we present the basic idea of adjusting nodes' equilibrium strategy based on estimation of network conditions without full information. More details on this will be discussed in later part of this paper. To the best of our knowledge, there is very little work on the incomplete cooperative game theory in wireless networks. In [9, 10], authors used the concept of incomplete cooperative game theory in wireless networks for first time and proposed the G-MAC protocol for the same. However, their proposed scheme is not suitable for all traffic conditions, especially, nonsaturation traffic condition which is most likely in sensor networks. In [11] authors presented a virtual CSMA/CA mechanism to handle the nonsaturation traffic condition which is too heavy and complex for the sensor networks.

We also work on similar baseline and present our suboptimal solution for an energy efficient MAC protocol in wireless sensor networks. In short, the main contributions of this paper are as follows.

(i) To present an analytical model of energy efficient MAC protocol based on incomplete cooperative game theory.

(ii) To present a suboptimal solution for energy efficient MAC protocol in WSN.

(iii) To present a performance evaluation study for the proposed solution.

The rest of this paper is organized as follows. Game theory and the incomplete cooperative game are introduced in Section 2, respectively. In Section 3, we present an improve backoff algorithm to improve the energy efficiency of MAC protocol in WSNs. Finally, the concluding remarks and future works are given in Section 4.

2. Game Theory and Incomplete Cooperative Game

Game Theory is a collection of mathematical tools to study the interactive decision problems between the rational players (In rest of the paper, we keep using terms "node" and "player" interchangeably) (Here, it is sensor nodes). Furthermore, it also helps to predict the possible outcome of the interactive decision problem. The most possible outcome for any decision process is "Nash Equilibrium." A Nash equilibrium is an outcome of a game where no node (player) has any extra benefit for just changing its strategy one-sidedly [12, 13]. From last few years, game theory has gained a notable amount of popularity in solving communication and networking issues. These issues include congestion control, routing, power control, and other issues in wired and wireless communications systems, to name a few.

A game is set of three fundamental components: A set of players, a set of actions, and a set of preferences. Players or nodes are the decision takers in the game. The actions (strategies) are the different choices available to nodes. In a wireless system, action may include the available options like coding scheme, power control, transmitting, listening, and so forth, factors that are under the control of the node. When each player selects its own strategy, the resulting strategy profile decides the outcome of the game. Finally, a utility function (preferences) decides the all possible outcomes for each player. Table 1 shows typical components of a wireless networking game.

Games can be classified formally at many level of detail, here we ingeneral tried to classify the games for better understanding. As shown in Figure 1, strategic games are broadly classified as cooperative and noncooperative games. In noncooperative games the player cannot make commitments to coordinate their strategies. A noncooperative game investigates answer for selecting an optimum strategy to player to face his/her opponent who also has a strategy of his/her own. Conversely, a co-operative game is a game where groups of player may enforce to work together to maximize their returns (payoffs). Hence, a co-operative game is a competition between coalitions of players, rather then between individual players. Furthermore, according to the players' moves, simultaneously or one by one, games can be further divided into two categories: static and dynamic games. In static game, players move their strategy simultaneously without any knowledge of what other players are going to play. In the dynamic game, players move their strategy in predetermined order and they also know what other players have played before them. So, according to the knowledge of players on all aspect of game, the noncooperative/co-operative game further classified into two categories: complete and incomplete information games. In the complete information game, each player has all the knowledge about others' characteristics, strategy spaces, payoff functions, and so forth, but all these information are not necessarily available in incomplete information game [13].

2.1. Incomplete Cooperative Game.

As we mentioned earlier, energy efficiency of MAC protocol in WSN is very sensitive to number of nodes competing for the access channel. It will be very difficult for a MAC protocol to accurately estimate the different parameters like collision probability, transmission

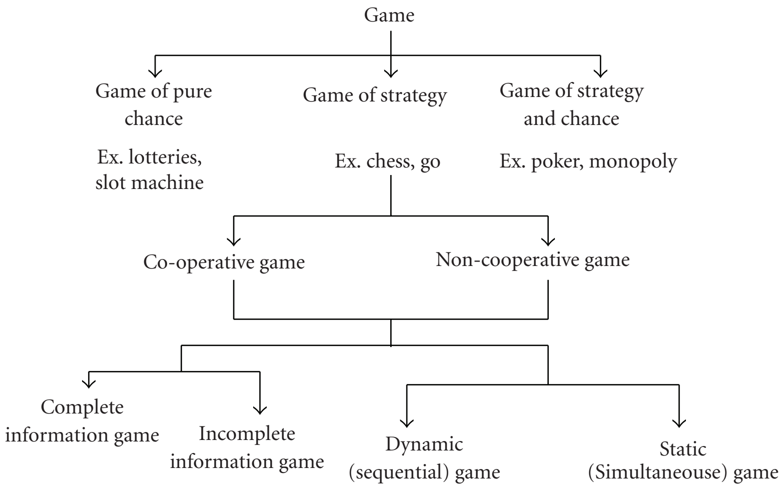

Figure 1: Classification of games.

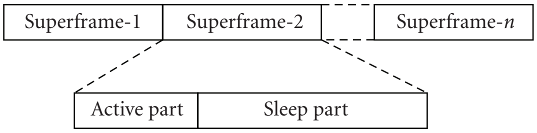

Figure 2: Active/sleep mechanism.

Table 2: Strategy table.

		Player 2 (all other n nodes)		
		Transmitting	Listening	Sleeping
Player 1 (Node i)	Transmitting	$(P_f, \overline{P}_f)$	$(P_s, \overline{P}_i)$	$(P_f, \overline{P}_w)$
	Listening	$(P_i, \overline{P}_s)$	$(P_i, \overline{P}_i)$	$(P_i, \overline{P}_w)$
	Sleeping	$(P_w, \overline{P}_f)$	$(P_w, \overline{P}_i)$	$(P_w, \overline{P}_w)$

probability, and so forth, by detecting channel. Because dynamics of WSN keep on changing due to various reasons like mobility of nodes, joining of some new nodes, and dying out of some exhausted nodes. Also, estimating about the other neighboring nodes information is too complex, as every node takes a distributed approach to estimate the current state of networks. For all these reasons, an incomplete cooperative game could be a perfect candidate to optimize the performance of MAC protocol in sensor networks.

In this paper, we considered a MAC protocol with active/sleep duty cycle (we can easily relate the "Considered MAC Protocol" with available MAC protocols and standards for wireless sensor networks, as most of the popular MAC protocols are based on the active/sleep cycle mechanism) to minimize the energy consumption of a node. In this MAC protocol, time is divided into super-frames, and every super frame into two basic parts: active part and sleep part, as shown in Figure 2. During the active part, a node tries to contend the channel if there is any data in buffer and turn down its radio during the sleeping part to save energy.

In incomplete cooperative game, the considered MAC protocol can be modeled as stochastic game, which starts when there is a data packet in the node's transmission buffer and ends when the data packet is transmitted successfully or discarded. This game consists of many time slots and each time slot represents a game slot. As every node can try to transmit an unsuccessful data packet for some predetermined limit (maximum retry limit), the game is finitely repeated rather than an infinitely repeated one.

In each time slot, when the node is in active part, the node just not only tries to contend for the medium but also estimates the current game state based on history. After estimating the game state, the node adjust its own equilibrium condition by adjusting its available parameters under the given strategies (here it is contention parameters like transmitting probability, collision probability, etc.). Then all the nodes act simultaneously with their best evaluated strategies. In this game, we considered mainly three strategies available to nodes: transmitting, listening, and sleeping. And contention window size as the parameter to adjust its equilibrium strategy.

In this stochastic game, our main goal is to find an optimal equilibrium to maximize the network performance with minimum energy consumption. In general, with control theory we could achieve the best performance for an individual node rather than a whole network, and for this reason our game theoretic approach to the problem is justified.

Based on the game model presented in [10], the utility function of the node (node i) is represented by $\mu_i = \mu_i(s_i, \bar{s}_i)$ and the utility function of its opponents as $\overline{\mu}_i = \overline{\mu}_i(\bar{s}_i, s_i)$. Here, $s_i = (s_1, s_2, \dots, s_{i-1}, \dots, s_n)$ represents the strategy profile of a node and $\bar{s}_i$ of its opponent nodes, respectively. From the aforementioned discussion, we can represent the above game as in Table 2.

As presented in [10], we define P_i and $\overline{P}_i$ as the payoff for player 1 and 2 when they are listening, P_s and $\overline{P}_s$ when they are transmitting a data packet successfully, P_f and $\overline{P}_f$

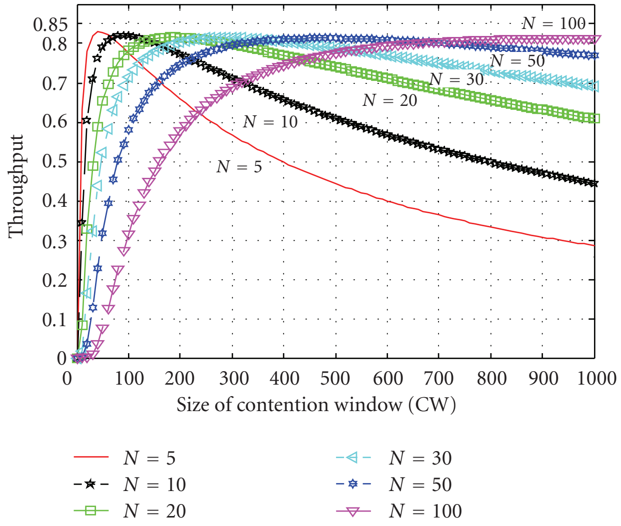

FIGURE 3: Relation between throughput and contention window.

when they are failed to transmit successfully, and P_w and $\overline{P}_w$ when they are in sleep mode, respectively. Whatever will be the payoff values, their self evident relationship is given by

$$P_f < P_i < P_w < P_S \tag{1}$$

and similar relationship goes for player 2. As per our goal, we are looking for the strategy that can lead us to an optimum equilibrium of the network. As in [10], we can define it formally as

$$\begin{aligned} s_i^* &= \underset{s_i}{\operatorname{argmax}} \overline{\mu}_i(\overline{s}_i, s_i) \mid (e_i < e_i^*), \\ \overline{s}_i^* &= \underset{\overline{s}_i}{\operatorname{argmax}} \mu_i(s_i, \overline{s}_i) \mid (\overline{e}_i < \overline{e}_i^*), \end{aligned} \tag{2}$$

where $e_i, e_i^*, \overline{e}_i$ and $\overline{e}_i^*$ are the real energy consumption and energy limit of the player 1 and 2, respectively. Now, to realize these conditions in practical approach we redefine them as follows

$$\begin{aligned} s_i^* &= \underset{(w_i, \tau_i)}{\operatorname{argmax}} \left\{ \begin{array}{l} \Big[(1-\overline{\tau}_i)\left(1-\overline{p}_i\right)(1-\overline{w}_i)(1-w_i)\tau_i\overline{P}_s \\ \quad +(1-\overline{\tau}_i)(1-\overline{w}_i)(1-w_i)\tau_i\overline{P}_i \\ \quad +\left(1-\overline{p}_i\right)(1-\overline{w}_i)(1-w_i)\tau_i\overline{\tau}_i\overline{P}_f \\ \quad +\overline{\tau}_i\overline{p}_i(1-w_i)\overline{P}_f \\ \quad +\overline{w}_i(1-w_i)\overline{P}_w \Big] \mid (e_i < e_i^*) \end{array} \right. \\ \overline{s}_i^* &= \underset{(w_i, \tau_i)}{\operatorname{argmax}} \left\{ \begin{array}{l} \Big[(1-\overline{\tau}_i)(1-\overline{w}_i)(1-w_i)\tau_i P_s \\ \quad +(1-\tau_i)(1-\overline{w}_i)(1-w_i)P_i \\ \quad +\tau_i\overline{\tau}_i P_f + w_i(1-\overline{w}_i)P_w \Big] \mid (\overline{e}_i < \overline{e}_i^*). \end{array} \right. \end{aligned} \tag{3}$$

Here, we define τ_i and $\overline{\tau}_i$ as the transmission probability of the player 1 and player 2, respectively. Similarly, w_i and $\overline{w}_i$ represents the sleeping probability of player 1 and player 2 while $\overline{p}_i$ is the conditional collision probability of player 2. As shown in Table 2, there are three strategies for both the players. First, player 1 transmits a packet with a probability $(1-\overline{\tau}_i)(1-\overline{w}_i)(1-w_i)\tau_i$, whose payoff is P_s. Second strategy of player 1 is listening with a probability $(1-\tau_i)(1-\overline{w}_i)(1-w_i)$, whose payoff is P_i. Third strategy of player 1 is sleeping with a probability $w_i(1-\overline{w}_i)$, whose payoff is P_w. Finally, when both the players transmits simultaneously, their payoff are P_f, and $\overline{P}_f$, respectively. Similarly, we can also calculate the probabilities of different strategies for player 2.

From the strategy table and (3) we can see that every node has to play its strategies with some probabilities as here the optimum equilibrium is in mixed strategy form. In mixed strategy equilibrium, it is not possible to reach an optimum solution with one strategy so players have to mix two or more strategies probabilistically. In this paper, players have three strategies: transmitting, listening, and sleeping and probabilities for selecting these strategies represent as P_{Tran}, P_{List}, and P_{Sleep}, respectively. Their relationship is given by

$$P_{\text{Tran}} + P_{\text{List}} + P_{\text{Sleep}} = 1. \tag{4}$$

In addition, we can observe from the above equations that players can achieve their optimal response by helping each other to achieve their optimal utility. So the nodes have to play a cooperative game under the given constrained of energy. Here, the players can obtain the mixed strategy-based optimum response by adjusting their transmission probabilities to the variable game states. The value of the transmitting probability can be adjusted by tuning contention parameters, such as the minimum contention window ($\text{CW}_{\min}$), the maximum contention window ($\text{CW}_{\max}$), retry limit (r), the maximum backoff stage (m), arbitrary interface spaces (AIFS), and so forth. For simplicity, we choose contention window (i.e., properly estimating the number of competing nodes) as tuning parameter for adjusting transmission probability of a node.

2.2. Estimation of Competing Nodes. In the proposed game, every node estimates the game state by anticipating the number of competing nodes from various parameters, especially, from transmitting probability p_{tr}. Many researchers have presented several performance and analysis models to calculate p_{tr}. However, majority of the work has neglected the contention counter freezing effect and considered only saturated traffic condition which is mostly suitable for WLAN and adhoc networks than sensor networks. Arguably, nonsaturation traffic condition is most likely traffic pattern in WSNs and need to be considered for a WSN MAC protocol designing as well. From [14] and other previous analysis results, we can show that the number (N) of competing nodes is the function of frame collision probability (p_c) of a competing node. Also, the probability p_c is constant and independent at each transmission attempt. A node transmits a data packet with the probability p_{tr} in a randomly chosen slot can be expressed as function of p_c, as in [14]

$$p_{\mathrm{tr}} = \frac{1}{(1-2p_c)(\mathrm{CW}_{\min}+1) + p_c\mathrm{CW}_{\min}\left(1-(2p_c)^m\right)/2(1-2p_c)(1-p_c) + (1-p_c)(1/\lambda^2-1)}. \tag{5}$$

Here, λ represents the traffic condition when $\lambda = 1$ every node always has a packet to transmit (i.e., Saturated traffic condition). Equation (5) also considered the freezing effect of backoff counter. So, from (5) it is clear that $p_{\mathrm{tr}} = p_{\mathrm{tr}}(p_c, m, CW_{\min}, \lambda)$, and depend on p_c. The relation between p_{tr} and p_c is given by

$$p_c = 1 - (1 - p_{\mathrm{tr}})^{n-1}. \tag{6}$$

Here, n denote the number of the nodes. After Substituting (5) into (6), and simplifying the equation with respect to n, as in [15], the simplified equation is given by

$$n = 1 + \frac{\log(1 - p_c)}{\log(1 - p_{\mathrm{tr}})}. \tag{7}$$

Now, by monitoring the channel all the nodes can independently measure the p_{tr} and p_c, hence, can estimate the value of n as well. Equation (5) is the simple form of p_{tr} as for the simplicity we neglected the retry limit. The channel is an ideal and introducing no error to the reception of a packet other than collision. Also, capture effect is not considered.

During the active part of the "considered MAC" protocol, every node is in wake up mode for any possible communication with the neighbors. So, the nodes do not have to waste any additional energy for aforementioned estimation mechanism. This estimation mechanism is implemented by adding three additional counters in the system. These three counters are transmitted fragment counter (TFC) which counts the total number of successfully transmitted data frames; acknowledge failure count (AFC) which counts the total number of unsuccessfully transmitted data frames, and slot counter (SC) which counts the total number of experienced timeslots. With these three counters we can estimate the p_{tr} and p_c, and hence the number of competing nodes n, can be presented as in [11]

$$\begin{aligned} p_{\mathrm{tr}} &= \frac{\mathrm{TFC} + \mathrm{AFC}}{\mathrm{SC}}, \\ p_c &= \frac{\mathrm{AFC}}{\mathrm{TFC} + \mathrm{ACF}}. \end{aligned} \tag{8}$$

This estimation mechanism gives good approximation but not the accurate results. There are some methods, especially [15, 16], to name a few, to accurately predict the number of competing nodes in the networks. In [17], authors presented batch and sequential Bayesian estimators to predict the number of competing nodes. In [15], authors presented two run time estimation methods named: "auto regressive moving average (ARMA)" and "Kalman Filters". These two methods are very accurate in predicting the number of competing nodes in saturation as well as in nonsaturation traffic conditions. However, all the methods presented in [15, 17] are too complex and heavy (in terms of energy consumption, etc.) to implement in sensor networks.

2.3. Motivation for Improved Backoff. As we mentioned earlier, estimating the game state accurately and timely are the key obstacles in formulating an incomplete cooperative game. Every node change its strategy by adjusting the contention window (i.e., properly estimating the number of competing nodes) and tries to achieve its optimal solution. However, according to [16] we cannot expect to find an algorithm that can give the theoretical optimum solution and runs in polynomial time, as the abovementioned problem has been proven to be NP-hard. So, if we allow each node to adjust its strategy after transmitting or discarding a packet rather than in each time slot we can relax the requirement on timeliness of the abovementioned game. Furthermore, we need a simple, light (in terms of energy and implementation) yet an effective suboptimal solution for the same. These challenges are the key motivation factors for us to introduce an improved backoff-based energy-efficient MAC protocol for WSNs, which can give a suboptimal solution to aforementioned incomplete cooperative MAC layer game.

2.4. Preliminaries. Based on our previous work [14], and using the parameters listed in Table 4, we show the relation of throughput and contention window in Figure 3 with different number of nodes.

As shown in Figure 3, the value of throughput firstly increases and then decreases for given number of nodes (n) as the value of CW increases from 1 to 1000. For the small number of nodes first throughput is increasing and then decreasing while for large number of nodes throughput is increasing slowly before its maximum point. The reason behind this is very obvious, at the lower number of nodes, less waiting time in backoff procedure during low contention window size. At the higher number of nodes, at first CW is too small to adjust with the number of nodes, hence high collision, but later it is adjusted with the number of nodes, so less collision and less waiting time in backoff procedure. However, all the nodes in the network achieved all most same maximum throughput as shown in Table 3.

Similarly, in Figure 4 we show the relation of average access time and contention window with different number of nodes. From Figure 4, we can observe that the average access delay time for different number of nodes is different. However, for given number of nodes, after certain length of contention window, the access delay time does not jitter and it is almost constant for rest of the contention window size. It

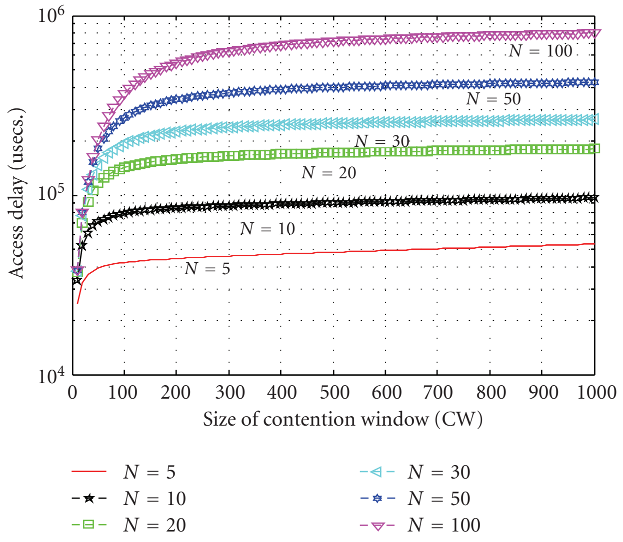

Figure 4: Relation between average access delay and contention window.

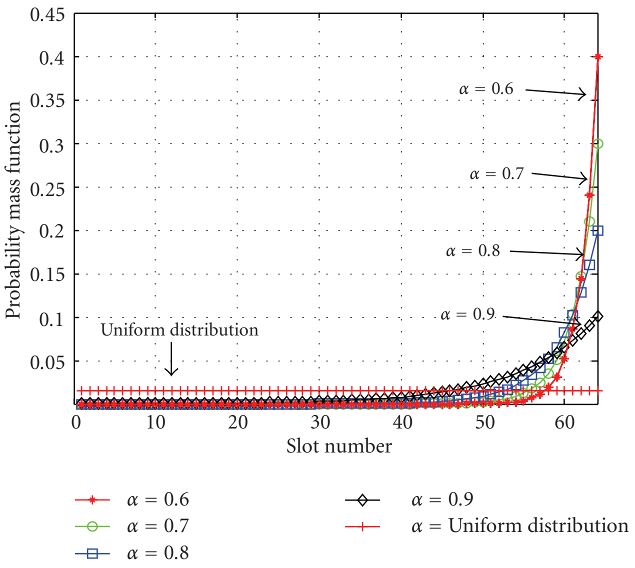

Figure 5: Difference between uniform and truncated geometric distributions (this result is taken from [14]).

Table 3: Number of nodes versus maximum throughput.

Number of Nodes (n)	Maximum Throughput	CW Size
5	0.825	45
10	0.820	97
20	0.819	195
30	0.818	300
50	0.817	450
100	0.816	800

is worth to note that the size of the superframe was kept fixed in order to obtain the results presented in Figures 3 and 4.

From the results presented in Figures 3, 4 and Table 3, we can observe that if we can adjust the size of the window or transmitting probability according to the number of competing nodes the maximum throughput can be achieved. This gives us an intuition to use Improved Backoff (IB) scheme for a suboptimal solution to incomplete cooperative game.

In this paper, we use a fixed size contention window, but a nonuniform, geometrically increasing probability distribution for picking a transmission slot (i.e., transmitting probability) in the contention window interval instead of traditional(here, traditional backoff procedure means CSMA/CA scheme with binary exponential backoff (BEB), unless and otherwise specified) backoff procedure. So, in this paper we present a suboptimal and a simple solution to achieve the optimum performance of a network.

3. Improved Backoff

In this section, we briefly introduce the improved backoff (IB), for more details on the same readers are refered to [14]. This is very simple scheme to integrate with any energy efficient MAC protocols for WSNs. This method does not require any complex or hard method to estimate the number of nodes. Furthermore, IB can easily accommodate the changing dynamics of WSNs.

3.1. IB Mechanism.

In contrast to traditional backoff scheme, IB scheme uses a small and fixed CW. In IB scheme, nodes choose nonuniform geometrically increasing probability distribution (P) for picking a transmission slot in the contention window. Nodes which are executing IB scheme pick a slot in the range of (1, CW) with the probability distribution P. Here, CW is contention window and its value is fixed. Figure 5 shows the probability distribution P. The higher slot numbers have higher probability to get selected by nodes compared to lower slot numbers. In physical meaning, we can explain this as: at the start node select a higher slot number for its CW by estimating large population of active nodes (n) and keep sensing the channel status. If no nodes transmits in the first or starting slots then each node adjust its estimation of competing nodes by multiplicatively increasing its transmission probability for the next slot selection cycle. Every node keeps repeating the process of estimation of active nodes in every slot selection cycle and allows the competition to happen at geometrically-decreasing values of n all within the fixed contention window (CW). In contrast to the probability distribution P, in uniform distribution, as shown in Figure 5, all the contending nodes have the same probability of transmitting in a randomly chosen time slot. As we mentioned earlier, IB uses a truncated, increasing geometric distribution, as presented in [14], and is given by

$$p = \frac{(1-\alpha)\alpha^{\mathrm{CW}}}{1-\alpha^{\mathrm{CW}}}\alpha^{-t_r} \quad \text{for } t_r = 1,\ldots,\mathrm{CW}. \tag{9}$$

Here, it is worth to note that IB scheme does not use timer suspension like in IEEE 802.11 to save energy and

Table 4: Simulation parameters.

Parameters	Values
$\mathrm{CW}_{\min}$	16
ACK packet size	24 Bytes
Data packet size	1024 Bytes
Nodes	5~100
Data rate	1 Mbps
Transmitting energy	50×10^{-6} J/Bit
Idle/listening energy	75×10^{-6} J/Bit

reduce latency in case of a collision. The only problem with the IB is fairness, however, for WSNs, fairness is not a problem due to two main reasons. First, overall network performance is more important rather than an individual node. Second, all nodes do not have data to send all the time (i.e., unsaturated traffic condition). Using IB may give us the optimum network performance as it reduces the collision to minimum.

3.2. Analytical Modeling of IB. In this section, we present the general frame work to model the backoff algorithm(in this paper, we use words "algorithm", "scheme", and "method" interchangeably). This frame work basically consists of three steps: finding the attempting probability for a node in backoff, finding the transition probability for a given channel state, and modeling the stationary probabilities of the channel state for required protocol details. Here, we model the channel efficiency with these basic steps. Based on our previous work [14], here we present the Markov chain model of IB with extra two states to model the nonsaturation traffic condition. A node may now wait in the idle state for a packet from upper layers before going into backoff procedure. This corresponds to a delay in the idle state and it is represented by upper left two sates in the Figure 6. The delay in the idle state is modeled geometric with parameter λ.

Figure 6 shows the state diagram of IB algorithm at an individual node. As we explained earlier, IB does not use contention counter suspension and there is only one stage (i.e., fixed backoff window). In IB, each node selects a contention slot with a geometrically increasing distribution as presented in [14] within the range of $(1, \ldots, \mathrm{CW})$, where CW is the fixed contention window size. This contention window is used as time unit for a node to detect the transmission of a frame from any other node. This time unit to be defined as "slot time" and this is different from the data transmission slot. Generally, data transmission slot is quite long compared to contention window slot. Using similar notation as in [18] for IB, here the state of each node is described by $\{j, k\}$, where j stands for the backoff stage, and k stands for the backoff timer value (For IB, $j = 0$ and $\max\{k\} = \mathrm{CW}$). Here, p_{CIB} represents as the collision probability and also p_{CIB} represents the probability of detecting the channel busy. Therefore, Figure 6 shows the one-dimensional discrete-time Markov Chain for IB at an individual node. In this Markov Chain, the nonnull one-step transition probabilities are as follows

$$\begin{gathered}
P\{0, k \mid 0, k+1\} = 1 - p_{\mathrm{CIB}}, \quad k \in (1, \mathrm{CW}), \\
P\{0, 1 \mid 0, k\} = p_{\mathrm{CIB}}, \quad k \in (1, \mathrm{CW}), \\
P\{0, k \mid 0, 1\} = p'_k, \quad k \in (1, \mathrm{CW}), \\
P\{-2, W_{-2} - 1 \mid -2, W_{-2} - 1\} = (1 - \lambda), \\
P\{0, k \mid -1, 0\} = \frac{\lambda}{p'_k}, \quad k \in (1, \mathrm{CW}), \\
P\{-2, 1 \mid -1, 0\} = (1 - \lambda), \\
P\{-1, 0 \mid -2, 1\} = \lambda, \\
P\{-1, 0 \mid 0, 1\} = 1 - p_{\mathrm{CIB}}.
\end{gathered} \tag{10}$$

The first equation in (10) indicates the backoff counter which is decremented if the channel is sensed idle. The second equation in (10) indicates the node defers the transmission of a new frame and enters stage 0 of the backoff procedure if it detects a successful transmission of its current frame or finds the channel busy or if it detects that a collision occurred to its current not successfully transmitted frame. The third equation in (10) indicates the node selects a backoff interval nonuniformly in the range of (1, CW) following an unsuccessful transmission. Rest of the equations shows the transition probabilities for two extra sates we added. Here, we take $\mathrm{CW}_{-2} = 2$ to introduce two extra states. The fourth equation in (10) represents the node waiting in the idle state for packet to arrive from the upper layer. The fifth equation in (10) shows the buffered packet enter to backoff procedure. The sixth and seventh equations in (10) represent the transition between buffer to idle state and back to buffer state according to availability of a packet, respectively. The last equation in (10) represents transition of backoff procedure to buffer state in case of a successful packet transmission.

In IB Scheme, a node is randomly selecting a contention window from the (1, CW) and transmit with the probability p'_k, where p'_k is based on the nonuniform increasing geometry distribution as given in (9) and define as

$$p'_1 < p'_2 < \cdots < p'_k < 1, \quad k \in (1, \mathrm{CW}). \tag{11}$$

To understand (11) readers are advised to refer Figure 5 where the different values of p'_k with different values of α are plotted. Now, similar to BEB scheme, we can define the probabilities of busy medium, idle medium and successful transmission in a time slot in IB scheme, respectively, as follows

$$\begin{gathered}
p_{\mathrm{IBb}} = 1 - \left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^n, \\
p_{\mathrm{IBi}} = \left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^n, \\
p_{\mathrm{IBs}} = n p'_k \left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^{n-1}.
\end{gathered} \tag{12}$$

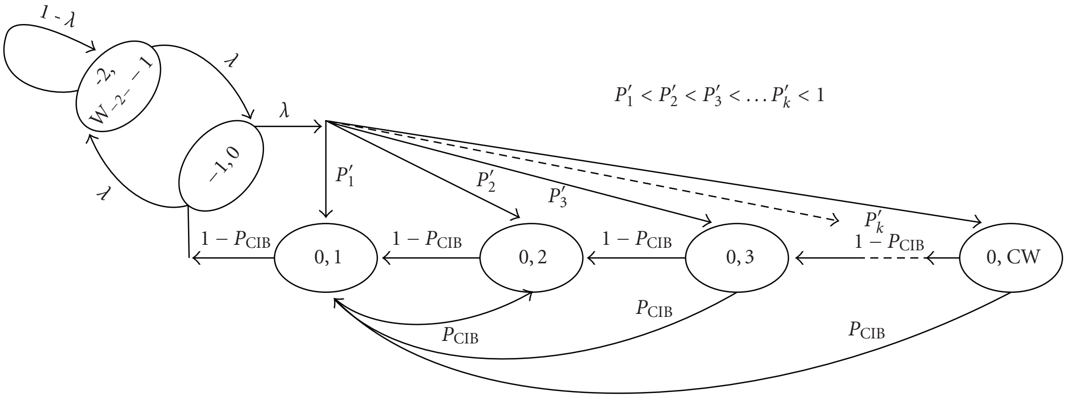

Figure 6: Markov Chain for IB Method.

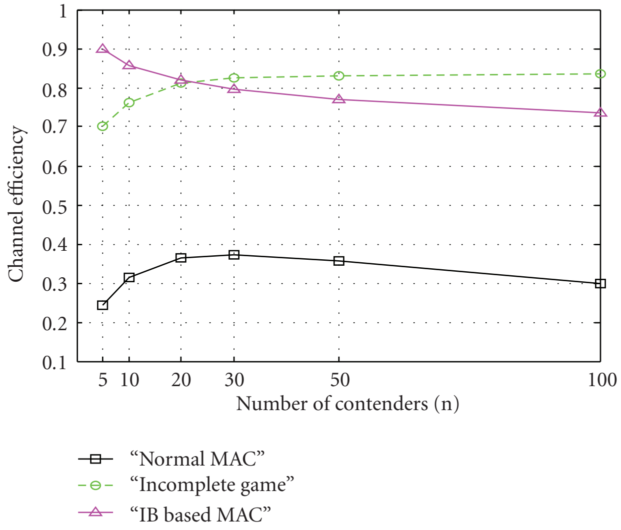

Figure 7: Shows the channel efficiency of "Normal MAC", "Incomplete Game" and "IB Based MAC".

Now, the probability of collision in IB is given by

$$P_{\mathrm{IBc}} = 1 - \left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^n - np'_k\left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^{n-1}. \tag{13}$$

Using aforementioned equations, we can define the channel efficiency as the fraction of time that the channel is used for successful transmission. The time that the channel remains empty or busy with collision is wasted. Here, successful transmission includes data frame with an acknowledgement. The simplified channel efficiency for IB scheme as in [14] is given by

$$\eta_{\mathrm{IB}} = \frac{np'_k\left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^{n-1}}{1 - (T_S - T_i)/T_S\left(1 - \left(p'_1 + \cdots + p'_k\right)\right)^n}. \tag{14}$$

3.3. Performance Evaluation. In this subsection we present, the performance comparison of incomplete cooperative game; that is, "Incomplete Game", our "considered" or "normal" MAC protocol, and IB-based MAC protocol in terms of channel efficiency, medium access delay, and energy-efficiency. The latter two protocols are the same in nature except for their backoff procedure. Here, we fixed the channel rate to 1 Mbps with an ideal channel condition. For the "normal" MAC protocol maximum retry limit is set to 6 ($m = 6$), minimum contention window is set to 16 (also for the IB Based MAC), and traffic model is set to nonsaturation. The backoff algorithm (BA) performed in a time-slotted fashion. A node attempts to attain the access the channel only at the beginning of a slot. Furthermore, all nodes are well synchronized in time slots and propagation delay is negligible compared to the length of an idle slot. For the performance evaluation, we carried out simulation in Matlab.

Here, we define network load in terms of the number of nodes that are contending for the access medium. Another approach is to consider total arrival packet rate to the network as an offered load. The main parameters for our simulation are based on [18] and listed in Table 4. For calculating the energy consumption in nodes, we choose ratio of idle: listen: transmit as 1 : 1 : 1.5, as measured in [19]. For the simulation results we do not consider the technology adopted at the Physical layer, however the physical layer determines some network parameter values like interframe spaces. Whenever necessary, we choose the values of the physical layer dependent parameters by referring to [18]. In case of "Incomplete Game", we assume that each node estimates the game state timely and accurately by detecting the channel. The results obtained here are the average values of our collected data.

As we have described in previous section, channel efficiency is mostly depends on number of active nodes and contention window size. As shown in Figure 7, at first "Normal MAC" (NM) gives high channel throughput at lower number of nodes. The reason is very obvious, less collision and low waiting time in backoff procedure, and as number of contenders increases channel throughput start decreasing. In contrast to NM, "IB-based MAC" (IBM) maintains high channel efficiency due to its unique quality of collision avoidance among the competing nodes. In IBM,

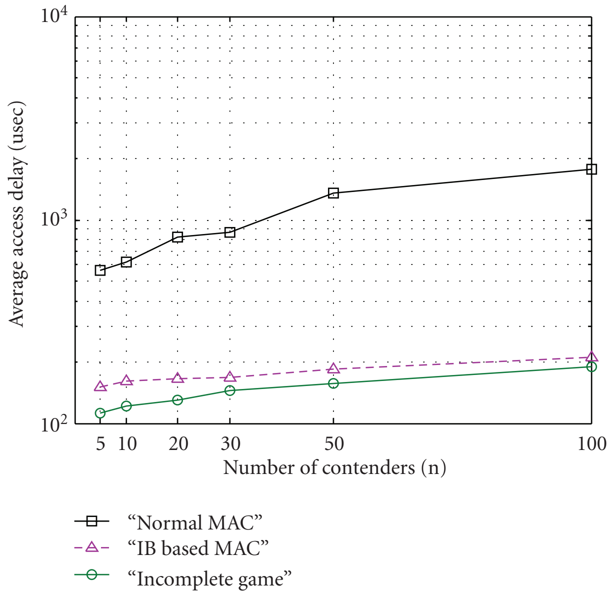

FIGURE 8: Average access delay versus number of nodes.

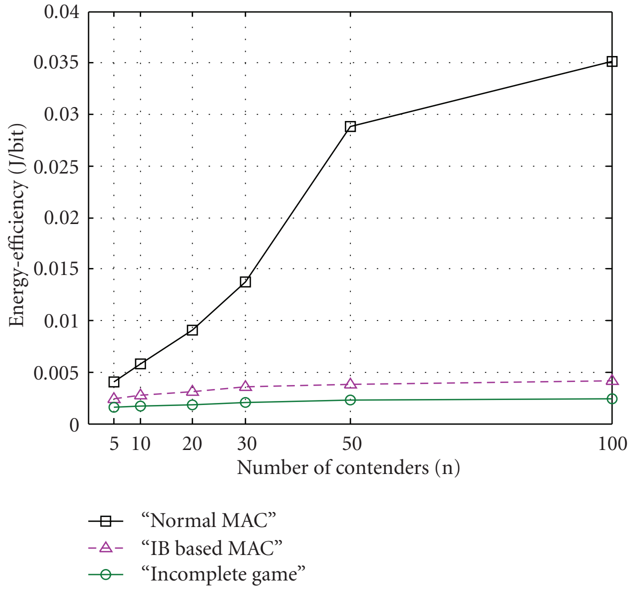

FIGURE 9: Energy-efficiency versus number of nodes.

most of the nodes choose higher contention slots while very few nodes selects lower contention slots, hence less or no collision and low waiting time in backoff procedure. For "Incomplete Game" channel efficiency almost keep constant after 30 nodes, as each node can adapt to the variable game state and choose corresponding equilibrium strategy. At start, it shows lower channel efficiency because contention window is still too big for given number of nodes.

Figure 8 shows the average medium access delay performances of NM, Incomplete Game and IBM. Here, medium access delay is defined as the time elapsed between the generation of a request packet and its successful reception. In NM scheme, as a large number of stations attempt to access the medium, more collision occurs, the number of retransmissions increases and nodes suffer longer delays. In IBM, as we expected access delay is very low compared to NM. This is because of low or no collision and less idle waiting time in backoff procedure. In "Incomplete Game", access delay performance is far better than "NM", and comparable with "IBM", as it can easily adapt the variable game state and choose the corresponding equilibrium strategy by adjusting contention window according to number of nodes.

Figure 9 illustrates the impact of CW on energy efficiency of NM, incomplete game, and IBM schemes. Here we define the energy efficiency as energy required to successfully transmit one bit of data packet.

From Figure 9, we can see that as number of nodes increases NM scheme waste more energy due to increase in collision and retransmission attempts. In contrast, IBM wastes very less energy due to its unique characteristics of collision avoidance. Similarly, "Incomplete Game" can also give the comparative performance to IBM, as it also reduces collision by adjusting its equilibrium strategy. Here it is worth to note that during the "Incomplete Game" all the nodes will switch to sleep mode when there is no communication. From all aforementioned results, we can see the superiority of IBM over NM. Accepting IBM as backoff scheme can increase the overall performance of an energy efficient MAC protocol to a large extends and we can also get the suboptimal solution for an incomplete cooperative game.

3.4. Applicability and Extendibility of the Incomplete Game.

In this paper, we use the concept of incomplete cooperative game to improve the performance of a WSN MAC protocol. Using the presented method here we can formulate a game for dynamic duty cycle adjustment in wireless sensor networks. With a proper fairness mechanism, it is also possible to extend our scheme to general wireless networks (i.e., IEEE 802.11). Furthermore, it is possible to extend our scheme to answer the selfish behavior of a node in IB and erroneous channel conditions as well.

4. Conclusions

In this paper, we used the concept of incomplete cooperative game to model the WSN MAC protocol for energy-efficient design. Moreover, we introduced IB for an energy-efficient MAC protocol in WSNs. It is very easy to implement in WSNs and also we do not need any complex estimation algorithm to calculate the number of nodes in the network. From the results, it is clear that IB can provide a suboptimal solution to an incomplete cooperative game.

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