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A NON-COOPERATIVE GAME APPROACH FOR POWER CONTROL MAC IN WIRELESS SENSOR NETWORKS

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Original scientific paper
In wireless sensor networks, efficient communication is the ultimate goal of a wireless medium access control (MAC) protocol. Concurrent transmission is one of the main ways to solve the issues of traditional MAC protocols with low throughput and accumulated delay in wireless sensor networks with high-load and intensive nodes. In this paper, a novel concurrent transmission MAC protocol is proposed that exploits channel capture allowing successful concurrent transmission to ensure effective communication. We use a power control algorithm based on non-cooperative game theory with incomplete information to achieve multiple link concurrent transmission on the same channel. Moreover, the Bayesian-Nash equilibrium theorem is introduced to determine its existence and uniqueness proof. Simulation results show that the protocol we proposed can perform well in an interference environment for concurrent data transmission. Significantly, the network throughput is improved and the data propagation delays are reduced therefore saving energy. Also, since we use the channel resources effectively, spatial reusing efficiency is improved significantly.

Keywords: *capture effect; concurrent transmission; game theory; MAC protocol; wireless sensor networks*

Pristup ne-kooperativne teorije igre za MAC kontrolu snage u bežičnim senzorskim mrežama

Izvorni znanstveni članak
U bežičnim senzorsim mrežama, uspješna komunikacija je glavni cilj protokola za kontrolu pristupa bežičnom mediju za prijenos podataka (MAC). Istovremeni prijenos je jedan od glavnih načina rješavanja pitanja tradicionalnih MAC protokola s malom propusnošću i akumuliranim zastojem u bežičnim senzorskim mrežama s visokim opterećenjem i intenzivnim čvorovima. U ovom se radu predlaže novi MAC protokol s istovremenim prijenosom koji koristi zahvat kanala omogućujući uspješni istovremeni prijenos da bi se osigurala učinkovita komunikacija. Koristimo algoritam kontrole snage temeljen na ne-kooperativnoj teoriji igre s nepoptpunim informacijama u svrhu postizanja istovremenog prijenosa višestruke veze na istom kanalu. Uz to, uvodi se Bayesian-Nashov poučak ekvilibrija za dobivanje dokaza o njegovom postojanju i jedinstvenosti. Rezultati simulacije pokazuju da protokol koji predlažemo može dobro funkcionirati u okruženju interferencije za istovremeni prijenos podataka. Značajno je da je poboljšan protok mreže i da su smanjeni zastoji u širenju podataka te je tako došlo i do uštede energije. Također, budući da efikasno koristimo resurse kanala, učinkovitost ponovne uporabe prostora značajno je poboljšana.

Ključne riječi: *bežične senzorske mreže; istovremeni prijenos; MAC protokol; teorija igre; učinak zahvata (apsorpcije)*

1 Introduction

The wireless sensor network with high-load and node intensive attracts the attention across the whole world due to its wide application. It emerges as a focus of research in the field of wireless sensor networks. Its application puts forward some new challenges on the design of WSNs. Due to constraints of power budget and very limited bandwidth resources, in many cases, data must be sent to a sink through multiple hops stages. However, the reachable delivery rate is limited out of the interference from the transmitting nodes, resulting in great amounts of data accumulating due to the nodes. Also, because of its low communication capacity, WSNs expand the data transmission delay. The low network throughput causes energy inefficiency. The key to the solution of the inefficient communication in sensor network is to design an efficient MAC protocol [1].

Low throughput and high delay issues of traditional MAC protocols indicate that they are not suitable for node intensive sensor network applications. In this paper, we propose a new MAC protocol exploiting capture effect that commonly exists in sensor networks with high-load intensive nodes. Capture effect is related to wireless signal demodulation. It means that when a receiver has two signal inputs, the receiver only modulates the input with the stronger of the two signals. Depending on the modulation type and RF hardware, the capture effect occurs if the signal power numerical difference is 1 ÷ 3 dB when the nodes transmit to the receiver [2]. Channel capture effect successfully achieves concurrent transmission [3, 4].

Game theory is a branch of applied mathematics. The resource allocation method based on non-cooperative Game theory was successfully applied in wireless networks in [5 ÷ 8]. A novel concept performance of DCF was proposed without explicit cooperation among nodes in [9]. The paradigm of independent decision making and limited communication fits perfectly into the framework of non-cooperative game theory, especially in a game where all players share the same objective. Niyato et al. investigated energy harvesting technologies required for autonomous sensor networks using a non-cooperative game theoretic technique in [4]. In our work, we apply non-cooperative game theory with incomplete information to solve the problem of power control in wireless sensor networks because the nodes are cognitive and can make decisions intelligently. The efficient communication in WSN is helpful to extend application scopes, to heighten the effects of resource utilization and to save unnecessary waste.

The main contributions of this paper are as follows. We propose a novel MAC layer protocol for data-intensive sensor networks, called GCT-MAC. The GCT-MAC protocol which is based on non-cooperative game theory power control algorithm and exploits wireless channel capture effect is able to select the optimal transmission power of nodes in the network for concurrent transmissions. The GCT-MAC protocol breaks through the limit of concurrent transmission based on traditional MAC protocols, effectively improving energy efficiency and significantly improving the valuable resources of wireless channel spatial reuse efficiency.

2 Related work

Power control as a key technology to effectively use and manage wireless channel resources plays an irreplaceable role in any wireless sensor network. Introducing a power control mechanism to a MAC protocol reduces energy consumption and so effectively saves energy and extends the lifetime of the network. Several throughput-oriented transmission power control in MAC protocols were proposed in PCDC [10], POWMAC [11]. PCDC proposed a protocol which uses two frequency-separated channels for data and control packets. The protocol allows interference-limited concurrent transmissions in the vicinity. The POWMAC protocol [11] uses a single channel for both data and control packets. Data packets are transmitted after several RTS/CTS exchanges take place. It provides that certain interference margins are not exceeded at each transmitter-receiver pair, which enables the scheduling of multiple concurrent transmissions in the same vicinity.

In recent years, many researchers have begun to apply game theory to solve the power control problem in wireless network area [12,13,14]. Our work, using a non-cooperative game theory to solve power control problem in the high-load sensor networks, proposes an incomplete information power control algorithm which can make a node select the optimal power for concurrent transmission in the network. In the paper, we use each node's signal to noise ratio (SINR) as the utility function and we study the existence and uniqueness of Nash equilibrium. Simulation results show that the PCCTBNG-MAC protocol based on the power control algorithm not only improves the network throughput, but also reduces energy consumption.

Currently, there are two main categories of wireless sensor network MAC protocols: competition-based MAC protocol and scheduling-based MAC protocols. All nodes in MAC protocol sharing one channel are based on the random competition method. Channel use on demand is when the node has data to send, and occupies a wireless channel using a competition method. When data transmissions conflict, the data is resent according to some strategy. SMAC is a typical usage of a competition protocol based on carrier sense multiple accesses (CSMA) [15], which adds sleep mechanisms on IEEE802.11MAC and reduces the idle time to minimize node energy consumption. Neighbouring nodes organize a cluster, so that synchronization sleep time takes place, reducing latency by way of message passing. T-MAC protocol is based on the protocol S-MAC [16]. The difference is inserting a time slot TA between node activity slots. If nothing happens at in the TA time slot, nodes fall asleep. Compared to S-MAC, this reduces idle listening power consumption. However, it adds the issue of early sleeping. Other competition-based MAC protocols such as B-MAC, X-MAC, and WiseMAC put wake-up leading before each T-MAC protocol frame to ensure that nodes wake up in time to solve any early sleeping problem. Another category is based on pre-allocation MAC protocols, mainly the three forms: Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA). TDMA gives all the bands of period to one node. FDMA divides each frequency band into multiple channels, different nodes using different channels. By comparison, TDMA communication time is shorter, but network synchronization time increases. CDMA has zero delay when accessing a channel, has a high bandwidth utilization rate and can reduce the impact of hidden terminals. However, due to the high complexity of its completely centralized way of channel allocation, it is not applicable in all distributed wireless sensor networks.

The Wireless sensor network MAC protocol mentioned above is more focused on energy efficiency issues, but has not broken through the design strategy of traditional ad hoc network MAC protocols. Although the traditional MAC protocol has energy efficient property, performance at network throughput and transmission delay has been poor. Thus many scholars proposed a number of concurrent transmission MAC protocols, for example, MACA-P which adds an extra gap between the RTS / CTS and DATA / ACK packet to complete concurrent data transmission scheduling [17]. Although MACA-P solves the exposed node issue, improvement to the concurrent transmission opportunity comes at the price of memory cost and incompatibility.

Recently many researchers have applied capture effects to do concurrent transmission [3,18], and experiment on in real environments. Confirmed concurrent transmission based on the capture effect in a real environment can enhance throughput and reduce the transmission delay efficiently. However, most of the transmitting power based on concurrent transmission MAC protocols is from calculation, and few people can supply a power algorithm model. In this paper, we propose MAC protocol through non-cooperative game power control algorithm to select power, saving the energy consumption as well as improving network efficiency.

3 System model and theoretical analysis

3.1 Model description

In the paper, we apply non-cooperative game theory with incomplete information to solve the problem of power control in wireless sensor networks. Nodes transmitting concurrently are the players. Non-cooperative game theory determines how players together select their strategy to maximize benefits. Each node uses the minimum power for its concurrent transmission to achieve the highest signal to noise ratio. In concurrent transmission power selection, node power selection depends on the power selection strategy of other nodes. However, in a distributed sensor network, no node knows the power selection strategy of other nodes. Therefore, this paper uses an incomplete information dynamic game power control model. Because each node cannot freely increase its own power in order to achieve a successful transfer, it will not only increase the interference to other nodes, but also lead to its neighbour nodes increasing their power for interference transmission. In order to control the behaviour of non-cooperation, this paper designs a balanced game strategy. Assuming all nodes in the games are rational, in non-cooperative game strategy, all nodes doing concurrent transmissions will choose the best strategy for power transmission. The purpose of power control algorithm for a non-cooperative game is to achieve the largest utility with the lowest power cost. The paper proves Nash equilibrium existence in the non-cooperative power control game. That means no node can have additional utility by unilaterally changing the transmission power to reduce system costs.

The non-cooperative game theory model can be described in three elements.

(1) Participants set $\Gamma = \{1, 2, 3, \ldots, n\}$, which are n nodes transmitting concurrently in the network.
(2) $s = \{s_1, s_2, s_3, \ldots, s_n\}$, s_i is the strategy space for the i^{th} node (i.e. any node n_i can select the set of power values). In this paper, the minimum power is the minimum value to achieve capture effect.
(3) Strategy profile $S = \{S_1, S_2, S_3, \ldots, S_N\}$, is the set of strategies selected by all participants in the network according to their own utility function to maximize their benefits.

Any node n_i's utility function in the paper can be described as below. s_{-i} are the strategy sets of all nodes except for the n_i.

$$U_i(s_i, s_{-i}) = \frac{LR}{Ms_i} f(\gamma_i) \quad \frac{\text{bits}}{\text{joule}}. \tag{1}$$

γ_i is the Signal-to-Interference Noise Ratio (SINR) defined as follows:

$$\gamma_i = \frac{W}{R} \frac{h_i s_i}{\sum h_i s_i + \sigma^2}. \tag{2}$$

W is available spread spectrum bandwidth. R is transmission rate after spectrum spread. $\{h_i\}$ is path gain. σ^2 is variance of background noise. Assume under a certain path condition. s_i is the transfer power of n_i. Define net utility function as follows:

$$U_{\text{net}} = \begin{cases} U_i(s_i, s_{-i}) - C(s_i) & \text{transmitting} \\ 0 & \text{not transmitting} \end{cases}. \tag{3}$$

Define $C(s_i)$ as the cost function of s_i, according to the actual meaning of the payment function. When s_i increases, the value of the cost function increases as well. That means $C(s_i)$ is a monotonically increasing function. Consider two different nodes n_1 and n_2, their transmitting powers are S_1 and S_2, assuming when $S_1 << S_2$, increase same power values ΔS to the two nodes, can get the following equation

$$C(S_1 + \Delta S) < C(S_2 + \Delta S). \tag{4}$$

The impact from $S_1 + \Delta S$ to $C(s_i)$ far less than to the $S_2 + \Delta S$, let $C(1) = k(s_i)$, according to the Eq. (4), we can see $k(S_1 + \Delta S) < k(S_2 + \Delta S)$. Therefore, $C(s_i)$'s derivative is also a monotonically increasing.

3.2 Existence and uniqueness of the Nash equilibrium

Because transmission power choice of concurrent transmission in sensor networks is the problem of non-cooperative game theory with incomplete information, we can have the following result by using Bayesian Nash Equilibrium Method.

Theorem: Nash equilibrium exists and is unique in a non-cooperative game with incomplete information of concurrent transmission power control.

Proof: Let $f_{s_i}(x)$ be the probability density function of s_i, assuming that the node can carry out data transfer under any large power condition, that is when $s_i \rightarrow +\infty$, node transmission probability is 1, so we can have $\int_0^{\infty} f_{s_i}(x)\,\mathrm{d}x = 1$.

But a real world power game, in order to reduce costs as well as reduce power usage, does not allow the node forward at any big power value. So we should constrain the transmitting power to a certain range, where we can assume that when transmission power as $s_i \in [z_i, P_i]$, the n_i we will get the largest net utility. z_i is the power value when n_i reaches the capture effect threshold in order to transmit simultaneously. P_t is the maximum power when a node transmits. So a node transmits at power s_i and $s_i \in [z_i, P_i]$, then the probability that the nodes can transmit simultaneously can be given by

$$p(P_t) = \int_{z_i}^{P_t} f_{s_i}(x)\,\mathrm{d}x. \tag{5}$$

The probability of no transmission is $1 - p(P_t)$ (the case of no transmission is the power value which cannot reach capture effect threshold or greater than the power upper bound value). So the probability that any m nodes out of N nodes are active is given by,

$$P_m = \binom{N}{m} p(P_t)^m \left(1 - p(P_t)\right)^{M-m}. \tag{6}$$

Then the expected net utility of the i^{th} node transmitting is given by

$$E\left[U_i^{\text{net}}\right] = \sum_{m=0}^{N} (u_i(s_i, s_{-i}) - A(s_i)) p_m \,. \tag{7}$$

And because of $\sum_{m=0}^{N} \binom{N}{m} p(P_t)^m \left(1 - p(P_t)\right)^{N-m} = 1$, then the formula (7) is equal to $E\left[U_i^{\text{net}}\right] = \sum_{m=0}^{N} u_i(s_i, s_{-i}) p_m - C(s_i)$.

Let $U_i(P_t) = \sum_{m=0}^{N} u_i(s_i, s_{-i}) p_m$, then the expected net utility of the i^{th} is given by

$$E[U_i^{\text{net}}] = U_i(P_t) - C(s_i). \tag{8}$$

If the nodes are transmitting simultaneously, expected net utility is Eq. (8). If the node does not transmit the expected net utility is 0. The expected net utility of any node is given by

$$\begin{aligned} G_i(P_t) &= \int_{z_i}^{P_t} [U_i(P_t) - C(x)] f_{s_i}(x)\,\mathrm{d}x = \\ &= U_i(P_t)p(P_t) \int_{z_i}^{P_t} C(x) f_{s_i}(x)\,\mathrm{d}x. \end{aligned} \tag{9}$$

We denote the above equation as follows

$$B(P_t) = \int_{z_i}^{P_t} C(x)] f_{s_i}(x)\,\mathrm{d}x.$$

Then Eq. (9) can be written as

$$G_i(P_t) = U_i(P_t)p(P_t) - B(P_t). \tag{10}$$

From the Eq. (10) we can see that when the actual transmission power reaches the value of the upper bound, we get the same expected utility, i.e., $s_i = P_t$. Thus P_t is the power upper bound of nodes transmitting concurrently when the whole network can achieve maximum utility. That is, P_t is the solution to the following equation

$$U_i(P_t) - C(P_t) = 0. \tag{11}$$

For the Nash equilibrium solution, when upper bound $s_i = P_t$, we can get the same expected utility whether transmission is done or not. If the node transmitting concurrently obeys the upper bound of power P_t, then even without the information of other nodes' power values, the system can achieve the Nash equilibrium, and all nodes will achieve a stable state.

Let us suppose T_1, T_2 be transmission power of any node, of which T_1 is the solution to Eq. (11), T_2 is any power, and $T_1 \neq T_2$, then the average utility of the node when $s_i = T_1$ and $s_i = T_2$ is as follows

$$\begin{aligned} G_i(T_1) &= \int_{z_i}^{T_1} [U_i(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x = \\ &= U_i(T_1)p(T_1) - B(T_1). \\ G_i(T_2) &= \int_{z_i}^{T_2} [U_i(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x = \\ &= U_i(T_1)p(T_2) - B(T_2). \end{aligned}$$

We can get the following equation

$$\begin{aligned} & G_i(T_1) - G_i(T_2) = \\ & = [U_i(T_1)p(T_1) - B(T_1)] - [U_i(T_1)p(T_2) - B(T_2)]. \end{aligned} \tag{12}$$

Due to $U_i(T_1) - C(T_1) = 0$, then $U_i(T_1) = C(T_1)$ and we can get the following equation

$$\begin{aligned} & G_i(T_1) - G_i(T_2) = \\ & = [C(T_1)p(T_1) - B(T_1)] - [C(T_1)p(T_2) - B(T_2)] = \\ & = C(T_1)[p(T_1) - p(T_2)] - [B(T_1) - B(T_2)]. \end{aligned} \tag{13}$$

(1) When $T_1 > T_2$, Eq. (13) can be written as

$$\begin{aligned} & G_i(T_1) - G_i(T_2) = \\ & = \int_{z_i}^{T_1} [U_i(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x - \int_{z_i}^{T_2} [U_i(T_2) - C(x)] f_{s_i}(x)\,\mathrm{d}x = \\ & = \int_{T_2}^{T_1} [C(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x. \end{aligned}$$

Because $C(s_i)$ is monotone increasing function of power s_i, then $\forall x < T_1$, we get $C(x) < C(T_1)$. Therefore $G_i(T_1) - G_i(T_2) > 0$.

(2) When $T_1 < T_2$, Eq. (13) can be written as

$$\begin{aligned} & G_i(T_1) - G_i(T_2) = \\ & = \int_{z_i}^{T_1} [U_i(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x - \int_{z_i}^{T_2} [U_i(T_2) - C(x)] f_{s_i}(x)\,\mathrm{d}x = \\ & = -\int_{T_1}^{T_2} [C(T_1) - C(x)] f_{s_i}(x)\,\mathrm{d}x. \end{aligned}$$

Then $T_1 < x \leq T_2$, we get $C(T_1) < C(x)$. Therefore $G_i(T_1) - G_i(T_2) > 0$.

Based on the above two cases, we can see that for any power T_2, if $\forall T_2 \neq T_1$, then $G_i(T_1) > G_i(T_2)$, thus T_1 is the selected power when the network achieves the maximum net utility, no power except for T_1 can provide the expected utility. That is T_1 is the solution of an incomplete information power control of Nash equilibrium as well as the unique solution.

4 The proposed GCT-MAC protocol

We now describe the details of GCT-MAC protocol. The purpose of GCT-MAC design is to get high throughput, allowing nodes to do concurrent transmission under interference. In order to reduce the interference impact of concurrent transmission, we use the Non-cooperative Game Theory power control algorithm to make each node to select the optimal power to do concurrent transmission. This algorithm can make all links achieve maximum throughput under power saving. GCT-MAC includes three parts: channel capture, power selection and transmission control.

4.1 Capture channel

Traditional MAC protocol failed to make full use of the wireless signal receiver capture effect to explore the concurrent transmissions existing in wireless sensor networks. GCT-MAC protocol is a concurrent transmission MAC protocol which uses capture effects, does not use CSMA mode. A number of activity links doing data transmission simultaneously, greatly improve wireless channel reuse. In this part, each node needs to maintain a neighbour list and pre-calculate the power value z_i which can achieve capture effect threshold.

4.2 Power selection

When the sensor network does concurrent transmission, we can assume that the power value of each node achieves the capture effect threshold. We select any power value over z_i to make sure the transmission is a success. As each node does not know the situation of other nodes, it leads to incomplete information game theory. If the node transmission is at any high level power, this will not only increase interference to other nodes, but also the neighbour nodes will increase power to resist interference. Thus we have a non-cooperative situation. In order to control this non-cooperative situation, we use non-cooperative game theory with an incomplete information model of power control about Nash equilibrium solution to compliance with GCT-MAC protocol, and the nodes can select optimal power to achieve concurrent transmission. The specific process is as below.

Each sensor network node sends a message periodically to establish a local neighbour information table, which includes the value of message node ID, the value of local node's interference power, and the benefit of this transmit power. Each node puts the local interference power in the message and broadcasts to the neighbour nodes. When neighbour nodes receive the packet, the transmitter calculates the net utility in accordance with Eq. (3) and updates its neighbour node information table. When the node needs to transmit data, it will search for its neighbour node information table and calculate the required transmit power in accordance with Eq. (11). By the Eq. (11), P_t is the power value if the whole network achieves the greatest benefit when n_i is doing concurrent transmission. In this protocol cost function $C(s_i)$ is given by

$$C(s_i)=\frac{1}{h_i}s_i. \tag{14}$$

h_i is path gain when the node launching at power s_i. If we put Eq. (1) and Eq. (2) into Eq. (11) we can get required power value when the n_i is doing transmission.

4.3 Transmission control

GCT-MAC protocol aims to achieve concurrent transmission. In order to prevent strong interference from asynchronous transmission or multi-nodes concurrent transmission, strict control of media access is compulsory. In the protocol, media access control includes three processes-traffic monitoring, concurrency checks and interference assessment.

(1) Channel traffic monitoring

Before a node starts to transmit data, it will evaluate the channel environment by monitoring the current channel transmission. The implementation of flow monitoring is based on two mechanisms. First, the way to perceive a channel is based on the energy. Nodes start to transmit data when the channel is idle. Secondly, if the channel is busy, GCT-MAC will confirm the ongoing active links. The node will listen to the channel T_θ seconds and periodically sample n times on the idle channel assessment (CCA). If the sampled signal strength is much lower than the value of average background noise, channel is idle. Otherwise GCT-MAC will declare that the channel is in a busy state. If the node doesn't receive data packets within T_θ seconds, and channel is busy, the node will suspend transmission and retry after a random delay.

(2) Concurrent transmission check

The purpose of the concurrent transmission check is to evaluate if in the data to be transmitted the transmission link can succeed in doing concurrent transmission to the destination node under interference. Suppose node s_0 ready to transfer data to the node r_0, firstly, s_0 implement flow monitoring phase to estimate the channel conditions, and then determine the activity links. Assuming that currently exist K concurrent transmission active links, represented as a collection in the form of $K=\{(s_i, P_{s_i}, r_i) \mid 0\le i\le k\}$, s_i, P_{s_i}, r_i respectively present active links to the sending node and receiving node and transmission power. Due to hidden terminals issues, K collection does not include all other conflicts links from r_0 to s_0. Every s_i select the optimal power for transmission based on non-cooperative game theory with power control algorithm, the power control algorithm will determine whether the power can achieve Nash equilibrium which is calculated by s_0 SINR. If Nash equilibrium can be achieved, the node will transmit data, otherwise it will not transmit.

(3) Link interference assessment

When the transmitter passes the flow monitoring and the concurrency check, it exchanges RTS/CTS packet with the receiver. Exchanging RTS/CTS packets has two objectives. First, it is the same way as based on the traditional CSMA/CA MAC protocol, avoiding the conflict of two nodes sending data to the same node simultaneously. Second, a transmitter can achieve a link interference situation by exchanging information with the receiver, which determines the communication quality of links. The specific process happens after the concurrency check. The transmitter sends a RTS packet including the destination address to the receiver. The receiver will respond with a CTS packet including interference information and noise energy. The other nodes which want to transmit, will back off after detecting the RTS or CTS. If the receiver is receiving data from other nodes and meanwhile receiving a RTS packet, the node will not respond with the CTS packets to avoid transmission conflict.

5 Simulation results

We have evaluated the performance of the proposed GCT-MAC protocol via the simulation in which we compared it with IEEE 802.11 and MACA-P [17] in the OPNET network simulator. The aim of PCCTBNG-MAC designation is to improve spatial reusing efficiency of wireless channel through concurrent transmission, and use non-cooperative game theory power control algorithm to make nodes with the optimal power to achieve maximum throughput and effectively save energy. In the simulation we take into account network average throughput, average packet delay and average energy consumption of the three performance metrics. The following table shows the settings of the simulation parameters, which are compatible with the standard 802.11.

In our work, we simulate network throughput, data packet transmission delay and energy consumption mainly by changing the network load. Nodes use the fixed bit rate source. The traffic model from each node obeys a Poisson distribution and changes system load by changing the packet interval time. We suppose that each node has data frame to be constantly sent, i.e. the system is saturated. Simulation parameter settings are as follows.

Table 1 Simulation parameter settings

Parameter statement	Value	Parameter statement	Value
Data frame length	1024 bytes	Channel rate	1 MB/s
MAC heads length	224 bits	SIFS interval	10 us
ACK frame length	304 bits	DIFS frame interval	50 us
RTS frame length	352 bits	Minimum contention window	31
CTS frame length	304 bits	Maximum contention window	1023
PHY frame length	192 bits	Slot length	20 us

To simulate GCT-MAC protocol performance under normal circumstances, we distribute terminal nodes randomly in the network. We consider a 1000 × 1000 m area, with n nodes placed randomly. In the simulation, to make MACA-P protocol can give full play to the advantage of parallel transmission; the size of control gap used for MACA-P is 640B. Assuming there is m active links ongoing concurrent transmission. The simulation results can be obtained as follows.

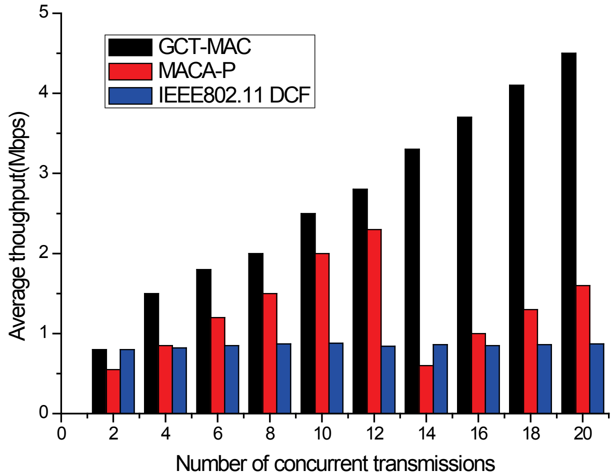

Figure 1 Average throughput (when n = 100, m = 20)

The simulation results are depicted in Figs. 1 and 2. When m is small, the average throughput of MACA-P is less than 802.11 and GCT-MAC. It is because of the lack of dynamic adjusting mechanism for the ACG. With increase of m, there are more chances for concurrent trans-missions, so MACA-P and GCT-MAC both perform better than 802.11. The larger the m, the higher average throughput GCT-MAC and MACA-P can achieve. However, GCT-MAC is significantly higher than MACA-P.

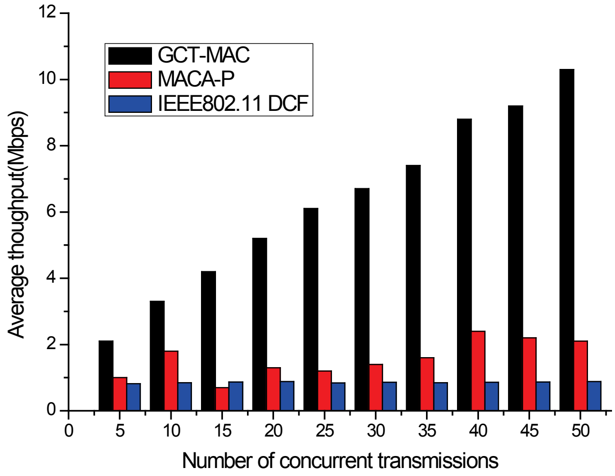

Figure 2 Average throughput (when n=200,m=50)

We can see that the average throughput of GCT-MAC can get 45Mbps when there are 20 sender-receiver pairs ongoing concurrent transmission, and with m increasing to 50, the average throughput increased more than 10Mbps. But due to 802.11DCF with carrier sensing mechanism prevents nodes from the concurrent transmission, so only one of them can access the channel at any time. As shown in Figs.1 and 2, there is not much change in the average throughput of 802.11 DCF. In the simulation, the source is saturated and always has packet to send. Experimental results show that compared with 802.11 DCF and MACA-P, the average throughput of GCT-MAC protocol has significantly improved. So GCT-MAC can better solve the traditional problem of low throughput of MAC protocol.

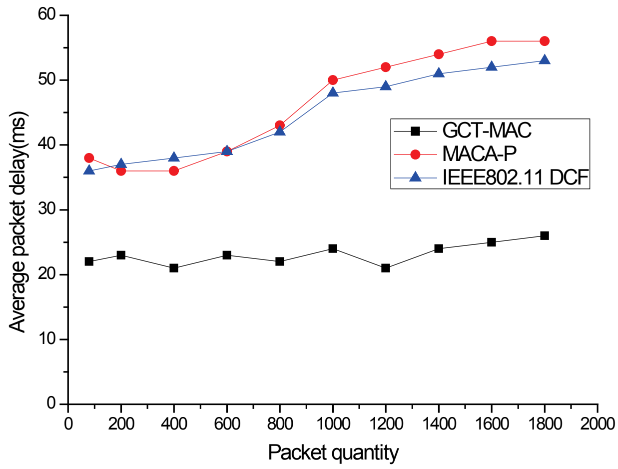

Figure 3 Average packet transmission delay (when n=100,m=20)

Figs. 3 and 4 show two simulation scenarios of average packet transmission delay. We can see there is only one effective link for transmission of 802.11DCF, with increasing the number of nodes in the network, channel competition becomes fierce. 802.11 DCF can get the channel after times of group competition, meanwhile, the networks increase the number of accumulated packets, the conflicts increase as well, which led high retransmission rate, Average packet transmission delay was in high state. Because MACA-P adds a control gap between RTS/CTS and DATA/ACK which allows neighbouring nodes to schedule their transmissions, data transmission is delayed by the controlled interval, which allows multiple sender-receiver pairs to synchronize their data transfers, thereby avoiding collisions.

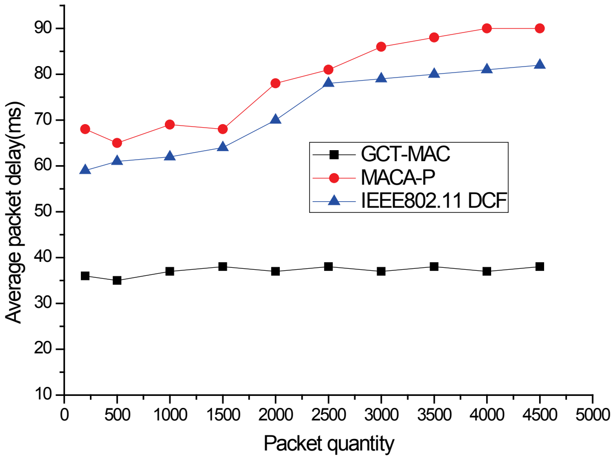

Figure 4 Average packet transmission delay (when n = 200, m = 50)

Figs. 3 and 4 show that GCT-MAC can realize multiple links transmit data simultaneously, which greatly reduces the average packet transmission delay. The experiment results show that two simulations were reduced by 59,22 % and 65,3 %. Simulation results show that the average delay of GCT-MAC protocol is much less than MACA-P and 802.11protocol.

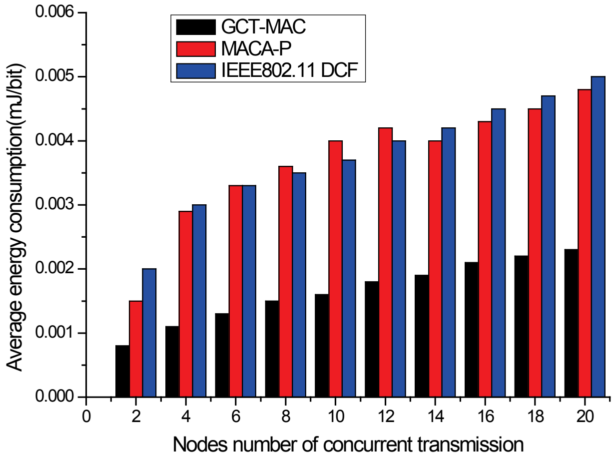

Figure 5 Average energy consumption (when n = 100, m = 20)

Figs. 5 and 6 analyzed the average energy consumption of network when m = 20 and m = 50 separately. From the simulation results, it can be seen that the average energy consumption of three protocols increase with the increasing number of nodes in the network. However, causes are different. In the case of 802.11 DCF protocol simulation, mainly because the network load increases, the conflict between the nodes will increase, the corresponding increase in opportunities for retransmission, so the node in the transmission process consumes more energy, and energy consumption grows. In MACA-P simulation, the control gap not only increases overhead of the protocol, but also destroys the continuity of RTS/CTS exchange and the subsequent DATA/ACK exchange causing data frame retransmission. So the average energy consumption of MACA-P is almost the same as 802.11.

As shown in Figs. 5 and 6, energy consumption growth of GCT-MAC is relatively slow. The reason for increased energy consumption is that nodes increase the transmission power to achieve capture effect and through power control algorithm to realize concurrent transmission. When the network has 20 pairs nodes ongoing concurrently, compared with 802.11 and MACA-P, GCT-MAC can reduce the average energy consumption to 50 %, and when m = 50 in the network to nearly 40 %. This result shows that GCTMAC can effectively save power consumption to extend the system life time.

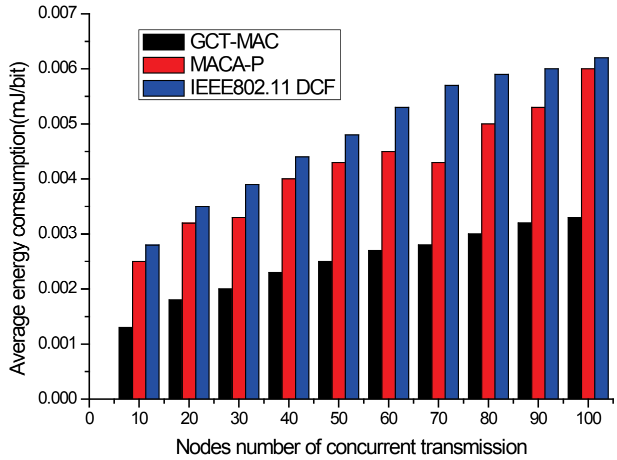

Figure 6 Average energy consumption (when n = 200, m = 50)

6 Conclusion

In this paper, we proposed a new concurrent transmission MAC protocol-GCT-MAC, by exploiting the impact of capture effect on MAC layer data transmission in the wireless sensor network with high-load and intensive nodes. In our work, we make power selection of n nodes transmitting simultaneously to be an abstract process of non-cooperative game with incomplete information. We apply Bayesian Nash equilibrium theorem to determine the existence and uniqueness proof of Nash equilibrium algorithm. We use non-cooperative games power control algorithm to achieve distributed control over the nodes to do concurrent transmission in the network. Adopting GCT-MAC protocol, after nodes achieve capture effect threshold, they can perform power selection according to non-cooperative game power control algorithm. Then we perform the channel traffic monitoring, concurrent transmission check and link interference assessment to complete GCT-MAC protocol. Simulation results show that GCT-MAC protocol significantly improves the network throughput and reduces data transmission delay and effectively saves power consumption so as to extend work time of nodes and life time of the wireless sensor network.

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