Game Theory Based Energy Efficient Hybrid MAC Protocol for Lifetime Enhancement of Wireless Sensor Network

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Abstract: Wireless Sensor Networks (WSNs) comprising of tiny, power-constrained nodes are getting very popular due to their potential uses in wide applications like monitoring of environmental conditions, various military and civilian applications. The critical issue in the node is energy consumption since it is operated using battery, therefore its lifetime should be maximized for effective utilization in various applications. In this paper, a Game theory based Hybrid MAC protocol (GH-MAC) is proposed to reduce the energy consumption of the nodes. GH-MAC is combined with the game based energy efficient TDMA (G-ETDMA) for intra-cluster communication between the cluster members to head nodes and Game theory based nanoMAC (G-nanoMAC) protocol used for inter-cluster communication between head nodes. Performance of GH-MAC protocol is evaluated in terms of energy consumption, delay and compared with conventional MAC schemes. The results obtained using GH-MAC protocol shows that the energy consumption is enormously reduced and thereby the lifetime of the sensor network is enhanced.

Keywords: Energy Consumption, Game Theory, GH-MAC, Lifetime.

1 Introduction

Wireless Sensor Network (WSN) encompasses numerous number of wireless nodes which sense, monitor and process data in adhoc fashion to facilitate the performance of task with utmost coordination. The nodes of the sensor are small, low cost, autonomous and operated by battery devices which has minimum energy capacity and processing capability [1, 2]. The group of nodes is known as clusters. Clustering scheme arranges the nodes in two domains: intra and inter cluster as depicted in the Fig. 1. The node senses the data and communicates with the cluster head (CH) node directly (single hop) in intra cluster while in inter cluster the CH node communicates to the sink either directly or through other CH node / nodes (multihop). The number of nodes competing for the radio channel in the inter - cluster is lesser compared to intra-cluster domain due to contribution of few CH nodes [3-6]. Highly localized and distributed protocols are required for different of communication, since communication of data consumes more energy than sensing and processing in a sensor network [7, 8].

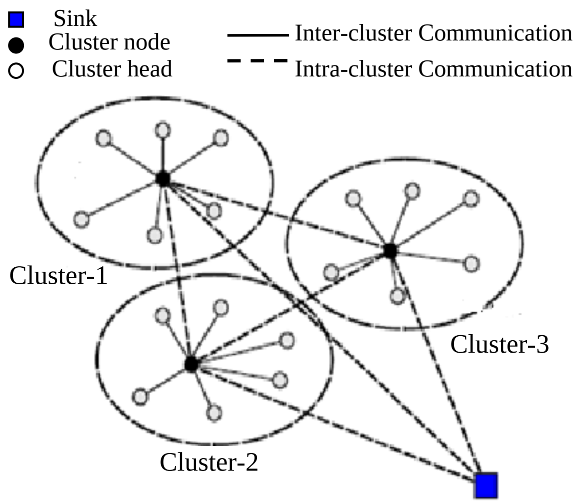

Fig. 1 Overview of intra and inter cluster domain of WSN [9].

Efficient operation of a sensor network is provided by the MAC layer since it avoids collision between data by not allowing two interfering nodes to transmit at the same time. The MAC schemes for wireless data communication is categorized into contention based and schedule based protocols. Based on the sensing of the channel, in contention based scheme, the sensor nodes keep their radio ON to transmit the message. The major disadvantage in using non-persistent carrier sense multiple access (np-CSMA) protocol is the nodes

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compete to share the channel which leads to collision from nodes beyond one hop and it leads to hidden terminal problem. In the case of schedule based MAC scheme, Time Division Multiple Access (TDMA) overcomes hidden terminal problem but it requires efficient scheduling of time to avoid idle listening of the channel. In conventional TDMA scheme, a node turns ON its radio during its assigned slot whether it has data to transmit or not, resulting in higher energy consumption. To reduce the energy consumption, Energy-efficient TDMA (E-TDMA) scheme is used, in which the node turns its radio OFF when it has no data to transmit [10]. The major energy wastage in np-CSMA and TDMA MAC schemes are collisions, overhearing, control packet overhead and idle listening to the channel [11, 12]. Therefore an efficient MAC protocol has to consume less energy and this is achieved by using nanoMAC protocol which has a sophisticated sleep algorithm and collision avoidance technique in CSMA. But the difficulty in decision making for data communication consumes more energy. Hence this paper suggests that a game theory is applied in ETDMA MAC protocol for intra cluster domain and nanoMAC protocol for inter cluster domain to reduce the time duration to take the decision and forward the data effectively which reduce energy consumption of the node.

Game theory based protocols for intra and inter cluster domain are combined known as game theory based hybrid MAC (GH-MAC) to enhance the lifetime of WSN. The highlight of GH-MAC protocol is that it adapts to the level of contention in the network either high or low. The analysis of the proposed GH-MAC protocol is evaluated in terms of energy consumption by the node analysis and compared with the conventional MAC protocol.

The rest of the paper is organized as follows. Section 2 deals with the system model to analyze the energy consumption. Game theoretic model for Hybrid MAC protocol is formulated in section 3. Simulation results and discussions are given in section 4. Finally, the conclusion of the work is provided in section 5.

2 Hybrid MAC Protocol

2.1 System Model

Node senses the data and communicates with the CH directly in the case of intra-cluster domain while the CH node communicates with the base station in inter-cluster domain. Fig. 1 illustrates the intra and inter cluster communication of WSN. In Hybrid MAC, the time is divided into large frames, every frame has three parts: idle slots, intra-cluster and inter-cluster. Fig. 2 depicts the frame structure of Hybrid-MAC protocol. The time slot is subdivided into mini slots equal to the number of nodes in a cluster and it carries one bit information of a node to determine whether the data is sensed or not.

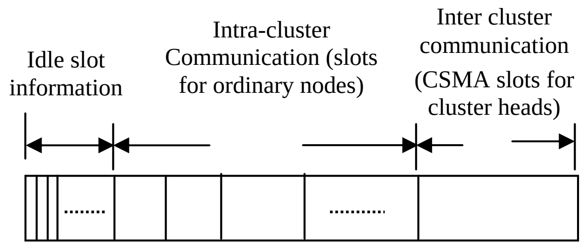

Fig. 2 Hybrid MAC frame structure.

If the node does not have sensed data, then the time slot will be allocated to the other node to transmit data. Before transmission, the CH node does Carrier Sense (CS) in the case of inter-cluster domain. The CH node goes to sleep if it fails to get the medium and randomly wakes up and listens to the channel again. This feature contributes to increasing the robustness of the Hybrid MAC protocol to synchronisation and topology changes while enhancing its scalability to contention.

2.2 Hybrid MAC Protocol for WSN

The Hybrid-MAC protocol is divided in two level of communication process: the first level is intra-cluster communication, i.e. between the cluster member to CH and the second level communication between the CHs. The operations in ETDMA is divided into two rounds, one is cluster set-up phase while the other is steady-state phase. The cluster set-up phase checks the nodes based on the energy level whether it can become CH node. The selected CHs broadcast an advertisement message to all nodes stating it is the new CH.

Then the other non-cluster head nodes which require minimum energy to communicate with CH joins together to form a cluster. With the formation of cluster, the system goes to steady-state phase. The categories of steady-state phase are contention period and frames. In the contention period, the nodes keep their radio ON while the CH builds TDMA schedule and transmits it to all nodes within the cluster. A data slot is allotted to each node in a frame. The duration of each frame is fixed. The data transmitted by a node is called source node. The source node transmits its data to CH within its allocated time by turning ON its radio and all other times the radio is kept OFF. The different states of inter-cluster communication are Arrive, Backoff, Attempt and Success state. In the arrive state, the node starts transmitting new data. It is notable that the entry of nodes in any one of the state, consumes energy. To reach the success state, all possible transitions from the arrival state to the success state is calculated. On the arrival of data, when a device finds the channel busy, it refrains from its transmission, and reaches the backoff state. When the channel is clear upon CS, the source CH transmits an RTS frame to the destination CH and it waits for a CTS frame and reaches the attempt state. On successful transmission of the RTS and reception of CTS, a transition to the success state is made. The success state represents a successful data exchange with the destination. When the RTS frame collides, the device returns to the backoff state and no new data transmissions are made during this failed period. Fig. 3 shows the entire communication process of Hybrid-MAC protocol.

2.3 Energy Consumption Analysis

2.3.1 For Intra-Cluster Communication

In the sensor field N sensors which are deployed in the permanent place. In intra-cluster domain, the process of communication between non-cluster head node and CH is divided into rounds consists of k sessions/frames. There are n_i source nodes in the i^{th} session /frame [13, 14]. The probability that a node has data to transmit is p, therefore n_i is a Binomial random variable.

$$\mathrm{E}(n_i) = Np = n \qquad i = 1, 2, \ldots, k. \tag{1}$$

Power consumption for transmit mode, receive mode, and idle mode are represented as P_t, P_r and P_i respectively. The communication between the CH and all other nodes is accomplished with non-persistent CSMA during the contention period.

If α is the throughput of non-persistent CSMA when there are N attempts per packet time then, each node transmits a control packet, and remains idle for the time $(N-1`)\frac{T_c}{\alpha}$. Hence, the energy consumption during the contention period for each node.

$$E_n = \frac{P_t t_c}{\alpha} + (N-1)\frac{P_i t_d}{\alpha} + P_r t_c \tag{2}$$

where t_c is time required to transmit/receive a control packet and t_d is time required to transmit/receive a data packet. The CH node receives control packets from all the nodes and dissipates the energy

$$E_{ch} = NP_r t_c + P_t t_c \tag{3}$$

The CH node also consumes the following energy during the i^{th} frame,

$$E_{ch} = n_i P_r t_d + (N-1)P_i t_d \tag{4}$$

Hence, in the i^{th} frame the system energy dissipated.

$$E_{fi} = n_i E_n + E_{ch} \tag{5}$$

The total energy spent in this domain during each round is computed as:

$$E_{round} = E = E_C + \sum_{i=1}^{k} E_{fi} \tag{6}$$

The average packet delay D between the source node and received CH node is given by [15].

$$D = \frac{Nt_c + n_i t_d + t_{ch}}{n_i} \tag{7}$$

where t_{ch} is the time required to transmit the control packet by the CH node.

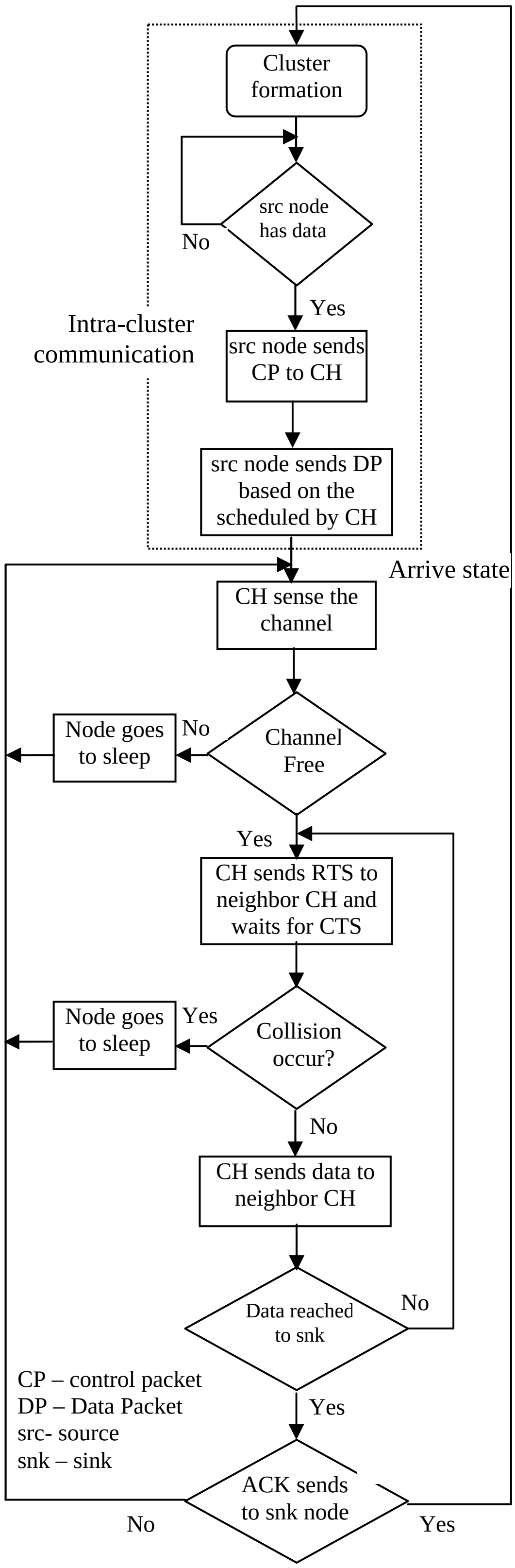

Fig. 3 System Model for Hybrid-MAC.

2.3.2 For Inter-Cluster Communication

In inter-cluster domain communication, the nanoMAC protocol is a type of CSMA/CA which is a powerful tool for medium access control. NanoMAC is a *p*-nonpersistent, i.e., with probability *p,* the protocol act as persistent and with probability 1–*p.* The protocol can refrain from sending even before CS and schedule a new time for *CS.* Nodes are not constantly listening and goes to sleep mode when the contention window is low. Then the node wakes up to sense the channel, if the channel is busy for a short but high confidence period before transmitting if the channel is detected vacant [16]. This feature makes the carrier sensing time short, even though the backoff mechanism is binary exponential and saves energy. Let the average transmitter energy consumption E_{tx} of a node with new data at the arrive state until the node reaches the success state, including of receiving an acknowledgement frame and is given by:

$$E_{tx} = E_{cs} + p_1 E(A) + (1-p_1)E(B) \tag{8}$$

where E_{cs} is the carrier sensing energy consumption when reaching the arrive state, *E(A)* and *E(B)* are the energy consumption on each visit by the node to attempt state and backoff state and is given by:

$$E\left(A\right) = p_2 E_s + (1-p_1)E(B) \tag{9}$$

and

$$E\left(B\right) = p_3 E(A) + (1-p_3)E(B) \tag{10}$$

E_s is the energy consumption upon attainment the success state from the attempt state. If p_1, p_2, p_3 are the different probabilities related to arriving in a certain state then the transmitter energy consumption can be simplified as:

$$\begin{aligned} E_{tx} &= t_{CS}M_{rx} + p_b\left(t_{bb} + \frac{t_r}{2}\right)M_{slp} \\ &+ p_b E(B) + (1-p_b)(1-p_{ers})\left(t_{bb} + \frac{t_r}{2}\right)M_{rx} \\ &+ (1-p_b)p_{ers}E(A) + (1-p_b)p_{ers}\left(t_{pr} + t_{RTS}\right)M_{tx} \\ &+ (1-p_b)(1-p_{ers})E(B) \end{aligned} \tag{11}$$

where M_{rx} is the receiver power consumption, t_{CS} is the time required for carrier sensing, p_b is the probability of finding channel busy during carrier sense, t_{bb} is the incremented backoff time, M_{tx} is the transmitter power consumption, M_{slp} is the sleep power consumption of transceiver and P_{ers} is the non-persistence value of nanoMAC. The t_{CS}, $t_r/2$, t_{pr} are the time required for carrier sensing, average random delay and to transmit a preamble respectively. The t_{bp} is the incremented backoff time and t_{RTS} is the time required to transmit an RTS frame. The receiver energy consumption E_{rx} for the reception of packet for being the proper destination is:

$$E_{rx} = E(I) = (\mu + P_s\theta)(P_s P_{senh})^{-1} \tag{12}$$

where *E(I)* is the energy requirement for each visit of node to idle state, μ represents the energy model transitions from state idle, θ represents the energy model transitions from state reply, P_s, and P_{senh} are the probabilities of no collision during RTS or CTS transmission [17, 18]. The average packet delay *D*, from the CH node/nodes to the base station is calculated.

$$\begin{aligned} D &= p_b\left(t_{bb} + \frac{t_r}{2} + E(B)\right) + (1-p_b) \\ &(1-p_{ers})\left(t_{bb} + \frac{t_r}{2} + E(B)\right) + (1-p_b)p_{ers}E(A) \end{aligned} \tag{13}$$

3 Game Formulation

Energy efficiency of MAC protocol in WSN is very perceptive to the number of nodes competing for the access channel. Estimation of the parameters like collision probability, transmission probability, and so forth are very difficult for a MAC protocol by detecting channel in wireless medium. To access the wireless channel in sensor networks, each node has a direct influence on its neighboring nodes. Therefore these interactions between nodes and aforementioned observations lead to use the concepts of game theory that could improve the energy efficiency as well as the delay performance of MAC protocol [19]. The repeated game is used in this paper and the repeated game is a class of dynamic games, in which a game is played numerous times and the players can observe the outcome of the previous game before attending the next repetition [20, 21]. In general the repeated game is defined as $G = \{N, p_i, E_i\}$, where *N* is the set of players (each node act as players), set of actions and payoff of each player *i* by p_i and E_i respectively. This game *G* is repeated up to *r* number of rounds. The proposed game is used to evaluate the energy consumption of nodes based on the traffic load probability. The energy conservation of GH- MAC is due to the avoidance of idle listening and turning OFF the CH radio when the nodes are going to sleep mode [22]. The game is formulated as the CH1 chooses its sleeping period $t_1 \in S$ and CH_2 chooses its sleeping period $t_2 \in S$ based on the traffic load and so on, then the set of all strategies chosen by all the nodes.

$$S = \{t_1, t_2, t_3 \ldots . t_n\} \tag{14}$$

In the repeated game, all the nodes to choose their individual strategies and the set of chosen result in some strategy profile. In every game, the node decides whether the sleeping time period based on the traffic level and the utility *U* of the game is:

$$U_i(S) = u_i\{t_i, t_{i-1}) \tag{15}$$

A utility function, describing player's preferences for a given player assigns a number for every possible outcome of the game with the property that a higher number implies that the outcome is more preferred. The higher number of participating nodes, the higher will be the utility.

4 Simulation Results and Discussions

The analysis of GH-MAC protocol is carried out using MATLAB 10. The parameters considered for the simulation is summarized in Table 1. The performance of the GH-MAC protocol is evaluated energy consumption and delay in terms of traffic load in the network.

Table 1 Simulation parameters.

Parameters	Value
Number of nodes	100
Area (m^2)	100 × 100
Transmitting Power (mW)	462
Receiving Power (mW)	346
Power for idle listening (mW)	330
Data rate(Mbps)	2
Data packet size (bytes)	1452
Control packet size (bytes)	52
Control frame size for nanoMAC (bytes)	18
Data frame size for nanoMAC (bytes)	41
Data frame payload of nanoMAC (bytes)	35
Device transmission distance (m)	100

4.1 Energy and Delay Analysis for Intra-Cluster Network

Fig. 4 shows the energy consumption with traffic load of intra-cluster domain for a single round. The energy consumption of three schedules based MAC protocol such as BMA, E-TDMA and G-ETDMA are compared with 20 nodes in a cluster and four sessions/round. It can be seen from the comparison, G-ETDMA provides better performance in terms of energy consumption than E-TDMA and BMA for the entire traffic load. The energy consumption of G-ETDMA is 22% less than E-TDMA and 35% less than BMA if traffic load is 0.4. The reason for this improved performance in G-ETDMA is by avoiding idle listening and also the CH nodes radio need not to be ON in the entire time slot.

The average energy consumption of non-cluster head nodes in a cluster for traffic load 0.4 with five sessions per round is shown in Fig. 5. G-ETDMA protocol performs better than E-TDMA and BMA schemes when the number of non-cluster head nodes handled by the CH node is less than 35. As the number of non-cluster head nodes in the cluster is larger, the contention period increases which result in greater energy consumption. Therefore, 33 non-cluster head nodes are optimum in a cluster adapting with G-ETDMA scheme.

Fig. 6 compares the three MAC techniques in terms of average packet delay. The delay is the time between the generation of a request packet and its successful reception. For higher traffic load, all the MAC schemes provide less delay. However as the traffic load approaches minimum, the average packet delay grows exponentially with BMA than G-ETDMA scheme. This is because in G-ETDMA protocol, the scheduling of nodes changes dynamically according to the traffic variations in the network. This greatly reduces the energy consumption of nodes due to avoidance of idle listening and thus maintains a good and lower delay performance. In BMA scheme, as a large number of nodes attempt to access the medium, more collision occurs, the number of retransmissions increases and nodes suffer longer delays.

4.2 Energy and Delay Analysis for Inter-Cluster Network

Fig. 7 shows the energy consumption analysis of single and multi hops network with and without game based nanoMAC protocols. It can be seen that from the energy analysis when the sink node is in within the characteristic distance of 100 m consumes less energy in a single hop transmission.

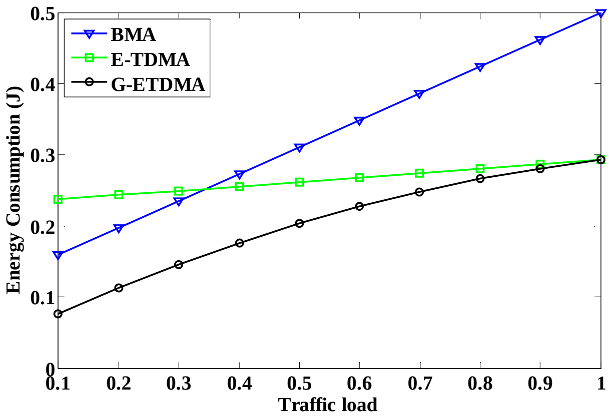

Fig. 4 Average Energy Consumption varies with traffic load (N = 20 and k = 5).

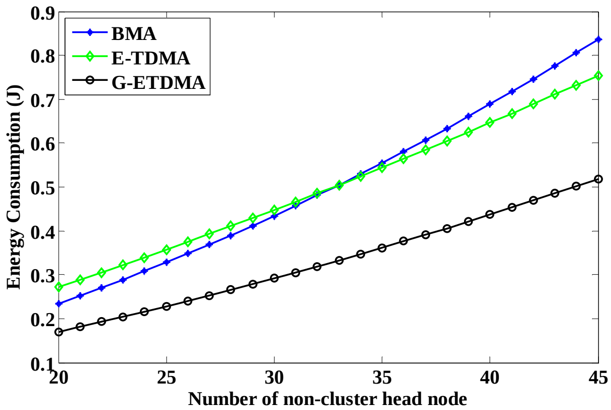

Fig. 5 Average total cluster energy consumption varies with N (k = 5 and traffic load is 0.4).

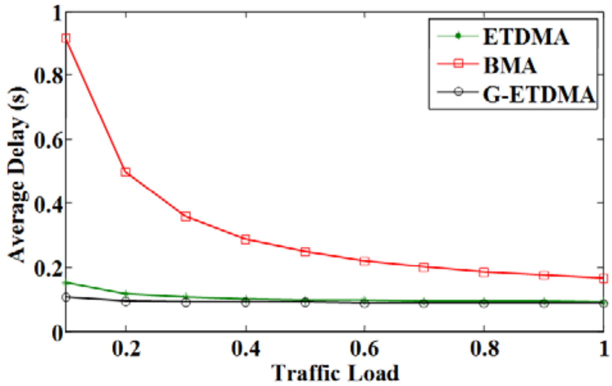

Fig. 6 Average delay varies with Traffic load.

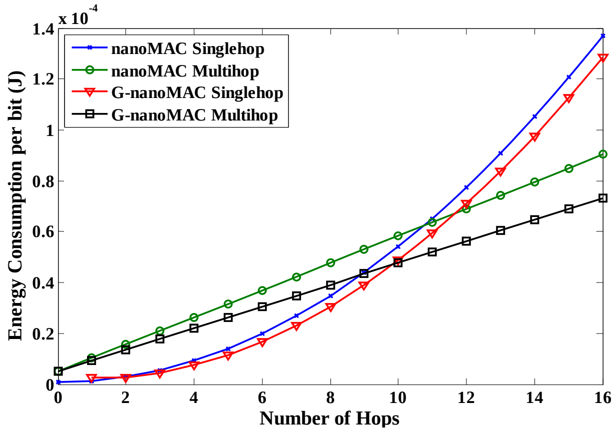

Fig. 7 Energy consumption varies with number of hops.

If the transmission distance is out of the characteristic distance then the multi hop communication is efficient and consumes less energy. From the Fig. 7, the G-nanoMAC consumes 1.6 times less energy than multihop within the transmission distance is 100 m. When the hop distance of about 100 m (i.e., ten hops) the energy consumption of single hop increases approximately by the factor of 0.5 than multihop because of path loss.

G-nanoMAC outperform up to the traffic load is 0.5 and beyond this traffic, the collisions may increase the energy consumption of the nodes. The comparison of normalized delay characteristics of nanoMAC and G-nanoMAC protocols are shown in Fig. 8.

The delay occurred at the reception of frame gradually increases with the traffic load due to the retransmission of entire frame when an error or collision occurring in this transmission period.

In G-nanoMAC protocol, a device sends ten data frames of 41 bytes each, an ACK frame for the same transmission period and retransmits only the lost/collided frame under the consideration of traffic load, thus the delay offered in the network is 1.2 times less compared to nanoMAC.

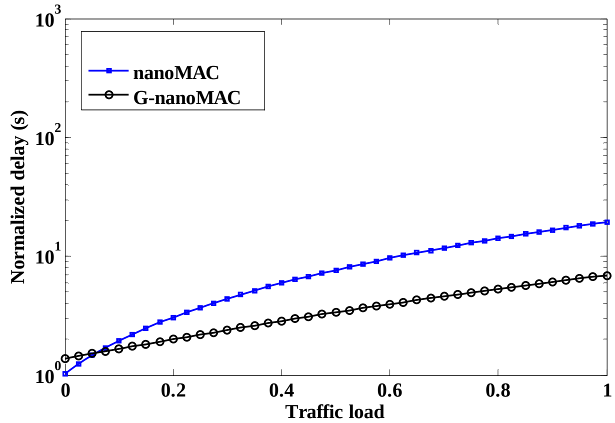

Fig. 8 Normalized load varies with traffic load.

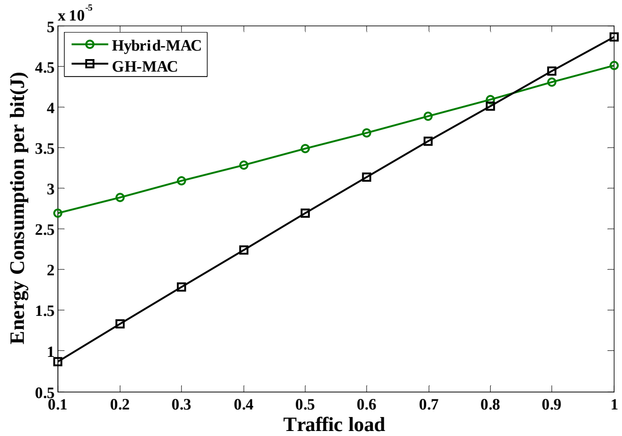

Fig. 9 Energy consumption per bit varies with traffic load.

4.3 Energy and Delay Analysis for Hybrid MAC Protocol

While combining two algorithms (G-ETDMA and G-nanoMAC), nodes need not to precede the two algorithms, the nodes can process the required algorithm based on the role (either cluster head or cluster member) by using different game strategies. Fig. 9 shows the energy consumption with traffic load for a hybrid MAC protocol and GH-MAC. The comparison is made for Hybrid-MAC and GH-MAC with 100 nodes in a network with the area of 100×100 m^2. GH-MAC is shown to provide better performance in terms of energy than Hybrid-MAC up to the traffic load is 0.85.

This is due to providing sleep time to CH based on the traffic and beyond this traffic all the nodes try to transmit their data which makes more collision and increase the energy consumption. A comparison of delay characteristics of Hybrid-MAC and GH-MAC protocols are shown in Fig. 10. Upon error or collision during this transmission period, the entire frame has to be retransmitted, hence the delay incurred in reception of frame gradually increases with the traffic load.

Table 2 Comparison of delay performance

Intra-cluster communication			Inter-cluster communication			Communication
Traffic load	Averag delay (sec)		Traffic load	Normalized delay (sec)		Average delay (sec)
	ETDMA [3]	G-ETDMA		nanoMAC [3]	G-nanoMAC	GH- MAC
0.2	0.04	0.10	0.2	2	1	0.2
0.3	0.03	0.09	0.3	3	1.5	0.21
0.4	0.02	0.08	0.4	4	2	0.22

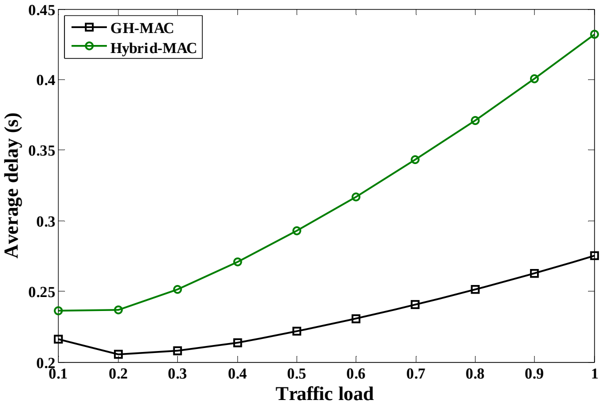

Fig. 10 Average delay varies with traffic load.

GH-MAC protocol is implemented by using G-ETDMA for intra-cluster communication and G-nanoMAC for inter-cluster communication. GH-MAC is consuming less time (less time delay) based on the game strategy which is compared with existing Hybrid MAC protocol as shown in Table 2. In the comparison, the delay in the proposed algorithm is slightly higher in intra-cluster communication due to large number of nodes competing for the radio channel however in the inter-cluster communication the delay is less due to fewer interaction among CH nodes when compared to [3]. However, the delay performance using hybrid MAC protocol of entire network is not analysed in [3].

5 Conclusion

In the GH-MAC protocol, energy and delay performance for offering traffic load has been discovered in the cluster based WSN. From these performances it is evident G-ETDMA protocol for the intra cluster communication achieves a 25 % reduction in energy consumption compared to BMA. It provides 15% less packet transmission delay by incorporating proper dynamic scheduling schemes. G-nanoMAC protocol offered better performance in inters cluster communication and its energy spent for data transmission is 20 % less than nanoMAC protocol. The delay performance for G-nanoMAC is considerably reduced by 12% without any degradation in throughput compared with nanoMAC protocol. For this efficient energy utilization in G-ETDMA and G-nanoMAC leads to energy reduction in GH-MAC for the entire communication process in WSN. This reduction in energy consumption and delay of the GH-MAC protocol can considerably extend the lifetime of the sensor network.

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