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Energy-Efficient MAC Protocols for Inter and Intra Cluster Wireless Sensor Network

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Abstract: - In WSN network, sensor nodes are battery operated and the power consumption become more important issue. The medium access control (MAC) protocol designed for the network must be stable and consume less energy. In this paper, we introduce a MAC protocol, named bit-map assisted (BMA) and NanoMAC protocol for energy efficiency at sensor nodes. In this paper, simulations of energy-efficient MAC protocols for inter and intra cluster wireless sensor network is presented. Finally some examples are presented with BAM and Nano MAC protocols for energy efficient wireless sensor networks.

***Index Terms*— Medium access controls (MAC) protocol, Bit-map assisted (BMA) protocol and NanoMAC protocol.**

I. INTRODUCTION

From last few decays, Wireless sensor Networks (WSN) have drawn the attention of researchers to deal with the theoretical and practical challenges in wireless communication [1]. The sensor nodes are typically battery powered, energy optimization and efficiency is extremely important in WSNs. Sensing, processing and communication are three key elements whose combination in one tiny device gives rise to a vast number of applications [2].

In sensor network, the communication of data consumes much more energy than sensing and data processing. Therefore, highly localized and distributed solutions for different levels of communication protocols are required. MAC layer enables the successful operation of the sensor network and its protocol tries to avoid collisions by not allowing two interfering nodes to transmit at the same time. Wireless sensor networks have application to the most diverse fields such as Environmental monitoring, warfare, child education, surveillance, micro-surgery, and agriculture [7]-[12]. Wireless sensor networks provide many opportunities, but also pose many challenges, such as the fact that energy is a scarce and usually non-renewable resource.

The rest of the paper is organized as follows. In section II, medium access control (MAC) protocol is explained. In Section III, explain the BMA MAC Protocol for Intra-Cluster Domain. In Section IV, explain the Nano MAC Protocol for Inter-Cluster Domain. In Section V, simulation results are explained. Finally, conclusions are drawn in Section VI.

II. MAC PROTOCOL

Medium Access Control (MAC) is used to avoid collisions by keeping two or more interface nodes from accessing the medium at the same moment, which is essential to the successful operation of shared-medium networks. The unique characteristics of WSNs require an energy-efficient MAC that is quite different from traditional ones developed for wireless voice and data communication networks. Four of the major performance metrics of MAC layer are power conservation, average end-to-end delay, throughput and control overhead.

MAC schemes for wireless networks are usually classified into two categories, contention based and contention-free. Contention-based schemes are widely applied to ad hoc wireless networks because of simplicity and a lack of synchronization requirements which is designed for minimum delay and maximum throughput. Contention-based schemes require sensor nodes to keep their radios on to receive possible incoming messages. These schemes are not energy-efficient due to idle listening. Contention-free schemes are scheduling-based schemes and try to detect the neighboring radios of each node before allocating collision-free channels to a link.

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Clustering scheme organizes the nodes of the sensor network into two virtual domains, such as intra-cluster and inter-cluster domain as shown in Fig.1. In the intra-cluster domain, the nodes within the cluster i.e. non-cluster head nodes sense the data and communicates with the cluster head directly. Since the radio channel has high contention in the intra-cluster domain, the TDMA based MAC (BMA) protocol is utilized for achieving high energy efficiency. In the inter-cluster domain, the cluster head node communicates with the base station directly (single hop) or through other cluster head nodes (multi hop). However, its channel contention is less compared to intra-cluster. Hence CSMA based MAC (NanoMAC) protocol; the more appropriate solution for the inter-cluster domain is used.

The frame structure of this MAC protocol is shown in Fig. 2. The time slot is divided into mini-slots which carry one-bit information of each node to determine whether they have the sensed data or not.

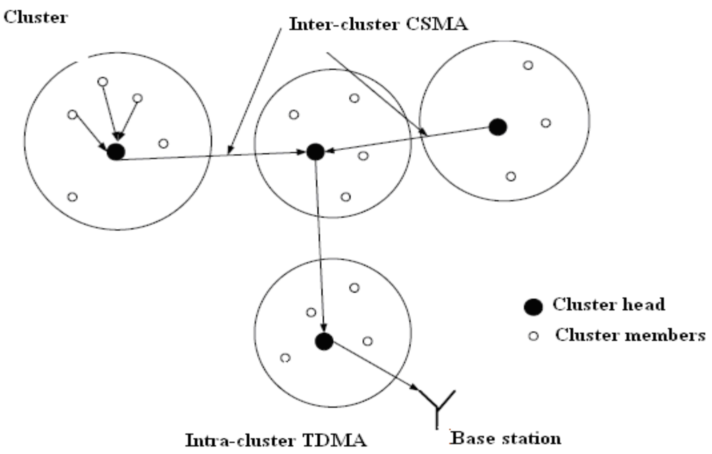

Fig: 1 System Model for MAC Protocol

If the node has no sensed data its time slot is allocated to other nodes that have data and the cluster head assigns this schedule to its members, in the intra-cluster domain.

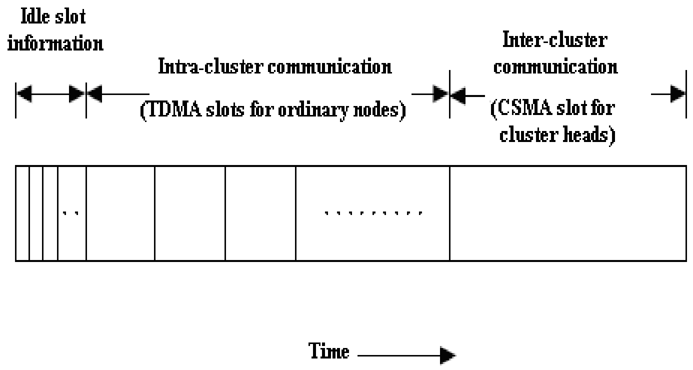

Fig.2: Frame Structure

III. BMA MAC PROTOCOL FOR INTRA-CLUSTER DOMAIN

The energy efficient TDMA (E-TDMA) scheme extends the conventional TDMA approach, a node turns its radio off when it has no data to transmit during its allocated time slots. In clustering approach, the data transmission of the non-cluster head nodes is organized into rounds. Each round consists of cluster set-up phase and steady-state phase as shown in Fig.3. Each session consists of a contention period, a data transmission period and idle period. During the contention period, all nodes keep their radios on. Using BMA MAC each node is assigned a specific slot to transmit a 1-bit control message if it has to send any data; otherwise, its scheduled slot remains empty.

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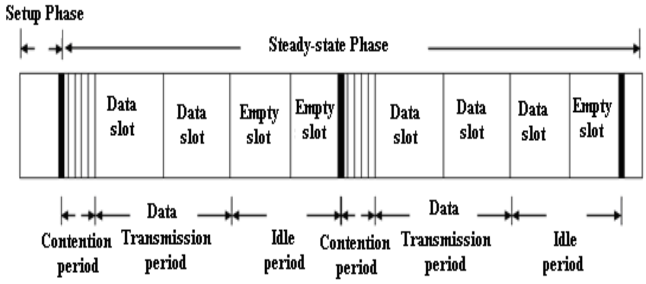

Fig.3: Steady-State Phase

After the contention period, the cluster head broadcasts its transmission schedule to the non-cluster head nodes in the cluster and the system enters into the data transmission period. If none of the non-cluster head nodes have data, then system goes directly to an idle period, which lasts until the next session [2]. The nodes keep their radios off during the idle periods to save energy.

Every source node using the energy during the single session is:

$$E_{sn}= P_tT_{cp}+ (N - 1)P_iT_{cp}+ P_rT_{ch}+ P_tT_d \qquad (1)$$

where N is the number of non-cluster head nodes within a cluster, P_t is the power consumption during the transmission mode, P_r is the power consumption during reception, P_i is the power consumption idle mode, T_{cp} is the time required to transmit/receive a control packet, T_d is the time required to transmit/receive a data packet and T_{ch} is the time required for BMA cluster-head to transmit a control packet. The energy dissipated during a single session by the non-source node is given by:

$$E_{in}= NP_iT_{cp}+ P_rT_{ch} \qquad (2)$$

During the contention period of the i^{th} session, cluster head node receives n_i control packets from non-cluster head nodes and stays idle for remaining contention slots. In the subsequent transmission period, the cluster head node receives n_i data packets from the non-cluster head nodes [3]. Hence, the energy expended in the cluster-head node during a single session is given as:

$$E_{ch}= n_i(P_rT_{cp}+ P_rT_d) + (N - n_i)P_iT_{cp}+ P_tT_{ch} \qquad (3)$$

Therefore, the total energy consumed in each cluster during the ith session is:

$$E_{si}= n_iE_{sn}+ (N - n_i)E_{in}+ E_{ch} \qquad (4)$$

Each round consists of k sessions, thus the total system energy dissipated during each round is computed as:

$$E_{round}= \sum{}^{k}{}_{i=1}E_{si} \qquad (5)$$

and hence, the average system energy expended during each round can be expressed as:

$$E = E[E_{round}] = k[n_iE_{sn}+ (N - n_i)E_{in}+ E_{ch}] \qquad (6)$$

The average packet delay D, is defined as the average time required for a packet to be generated by a source node and received by the cluster-head node and is given by:

$$D= (NT_{cp}+ T_{ch}+ n_iT_d) / (n_i) \qquad (7)$$

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IV. NANO MAC PROTOCOL FOR INTER-CLUSTER DOMAIN

In conventional np-CSMA scheme, a node with a frame to transmit senses the channel using carrier sense. If the channel is detected busy, the node waits for a random time. To minimize the energy consumption, NanoMAC protocol is suggested as a feasible solution for inter-cluster domain. NanoMAC protocol is of carrier sense multiple accesses with collision avoidance (CSMA/CA) type. The protocol will act as non-persistent and the protocol will refrain from sending even before CS and schedule a new time to attempt for CS. Nodes contending for the channel do not constantly listen for the channel, but sleep during the random contention window. The nodes will wake up to sense the channel, if the back off timer expires,. This feature makes the CS time for NanoMAC short, and saves the energy of sensor nodes to a greater extent [4]. With one request-to-send (RTS) and clear-to-send (CTS) reservation, a maximum of 10 data frames can be transmitted using the frame train structure as shown in Fig.4. The data frames are acknowledged by a single, common acknowledgement (ACK) frame that has a separate ACK bit reserved for each frame. In this way, only the corrupted frames are retransmitted and not the whole packet.

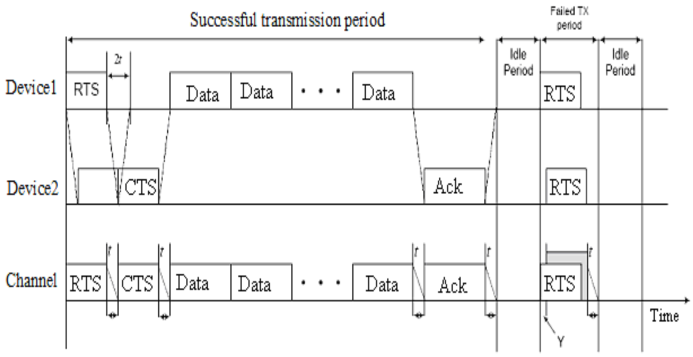

Fig.4: Transmission periods of NanoMAC Protocol

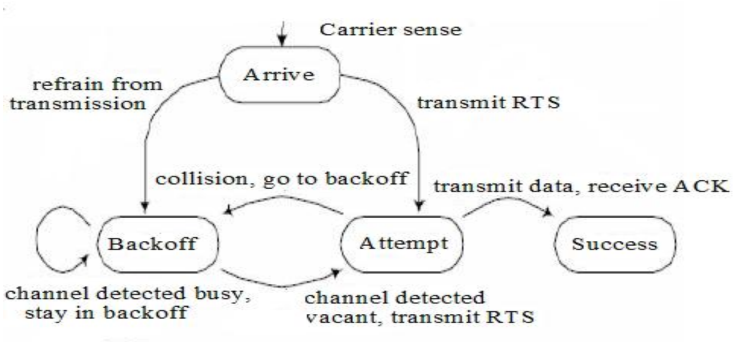

Fig. 5: Transmitter Energy Model of NanoMAC Protocol

If a device finds the channel busy, on data arrival, it refrains from its transmission, and goes to the back off state. The sensor node transmits an RTS frame to the destination node and it waits for a CTS frame and reaches the attempt state (if the channel is clear upon CS). On successful transmission of the RTS and reception of CTS, a transition to the success state is made. When the channel is detected busy, it stays in the back off state and the process repeats.

$$E_{TX} = E_{arrive} + P_{prob1}E(A) + (1- P_{prob1})E(B) \quad (8)$$

where, E_{TX} is the average transmitter energy E_{arrive} 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 back off state and is given by:

$$E(A) = P_{prob2}E_{success} + (1 - P_{prob2})E(B) \qquad (9)$$

and

$$E(B) = P_{prob3}E(A) + (1- P_{prob3})E(B) \qquad (10)$$

$E_{success}$ is the expected energy consumption upon reaching the success state from the attempt state and $P_{prob\{1,2,3\}}$ are the different probabilities related to arriving to a certain state [5].The transmitter energy consumption can be simplified as:

$$E_{TX} = T_{CS} M_{RX} + P_b(T_{bb} + (T_r/2))M_{slp} + P_bE(B) + (1-P_b)(1-P_{ers})(T_{bp} + (T_r/2))M_{slp} + (1-P_b)P_{ers}E(A) + (1-P_b)P_{ers}E(B) + (1-P_b)P_{ers}(T_{pr} + R_{TS})M_{TX} \qquad (11)$$

where T_{CS} is the time required for carrier sensing, M_{RX} is the receiver power consumption, P_b is the probability of finding channel busy during carrier sense, T_{bb} is the incremented back off time, $T_r/2$ is the average random delay, M_{TX} is the transmitter power consumption, M_{Slp} is the sleep power consumption of transceiver, T_{pr} is the time required for transmitting preamble, P_{ers} is the NanoMAC's non-persistence value, T_{bp} is the un-incremented back off time and R_{TS} is the time required to transmit an RTS frame. The receiver energy consumption of a packet for NanoMAC protocol is shown in Fig.6. This model takes the reception of data into account as the average probability of receiving the data correctly. Idle, Reply and Received are the three different states. After receiving an RTS packet, the destination node transits to state Reply and forwards the CTS packet to the source [5]. When the destination node receives the valid data packet from the source it reaches the received state and sends an ACK frame to the source node. When the CTS packet transmitted by the receiver collides it stays in idle state. The average receiver energy consumption E_{RX} listening for a transmission to detect and receive a packet for being the proper destination is given by:

$$E_{RX} = E(I) = (\mu + P_s\theta)(P_sP_{senh})^{-1} \qquad (12)$$

Here, the energy incurred in each visit of node to idle state is E(I), 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.

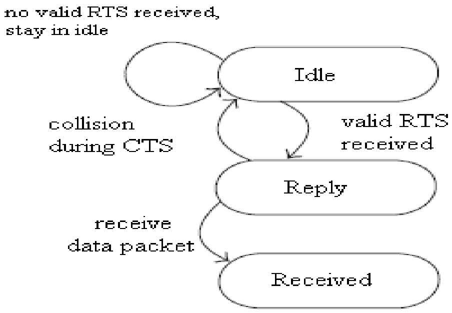

Fig.6: Receiver Energy Model of NanoMAC Protocol

The average packet delay D, from the cluster head to the base station is:

$$D = P_b(T_{bb} + (T_r/2) + E(B)) + (1-P_b)(1-P_{ers})(T_{bp} + (T_r/2) + E(B)) + (1-P_b)P_{ers}E(A) \qquad (13)$$

The channel throughput S, is defined as the average number of successful frame transmissions per time interval Tp and is given by:

$$S = (G(b + 1)(1 - P_{ers} + e^{-aG}P_{ers})) / (G(1 + (4 + P_{ers})a + 2b + c) + e^{-aG}P_{ers}) \qquad (14)$$

Here, the traffic intensity or normalized traffic offered to the channel is G, a is the normalized propagation time, b is the normalized control packets and c is the normalized ACK delay [3].

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V. SIMULATION RESULTS

1. Average intra-cluster energy consumption with traffic load using BMA Protocol

Fig. 7 shows the average intra-cluster energy consumption with traffic load for a single round. A comparison is made for the MAC schemes such as E-TDMA (Energy Aware TDMA) and BMA protocol. BMA is shown to provide better performance in terms of energy than E-TDMA. The main reason for energy conservation in BMA protocol comes from avoiding idle listening for transmission through the channel.

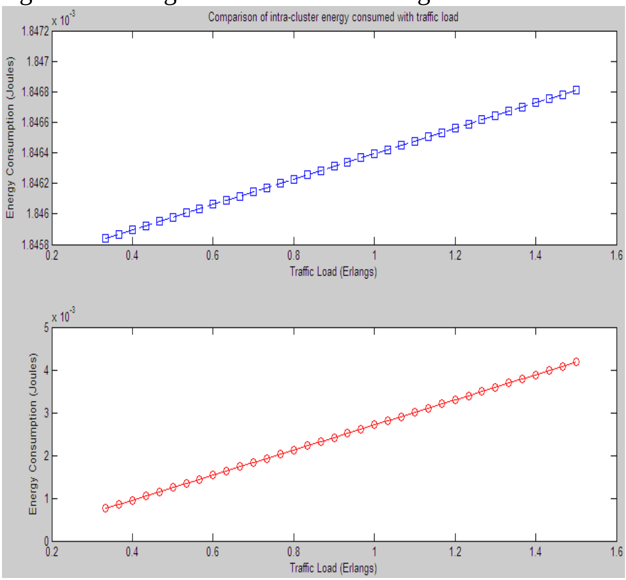

Fig.7: Comparison of intra-cluster energy consumed with traffic load

2. Intra-cluster average packet delay using BMA Protocol

Fig.8. compares the MAC techniques in terms of average packet delay. The BMA protocol clearly shows less average delay than E-TDMA. This is because in BMA protocol, the scheduling of nodes changes dynamically according to the traffic variations in the network.

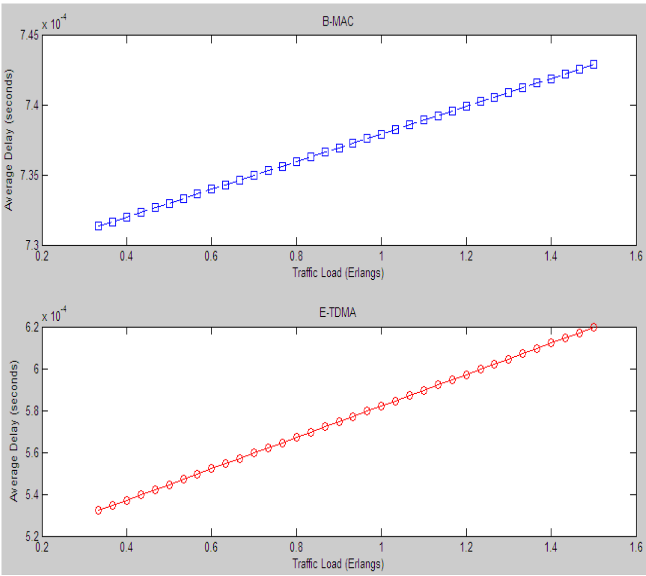

Fig. 8 Intra-cluster average packet delay

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3. Average intra-cluster energy consumption with traffic load using Nano MAC Protocol

Fig.9 illustrates the energy consumption in transmission of data as a function of traffic load for NanoMAC and E-TDMA scheme. NanoMAC protocol performs well even in periods of high traffic bursts and its energy consumption stays low by incorporating proper sleep schedules. Thus, NanoMAC protocol when used for inter-cluster domain can achieve better energy efficiency.

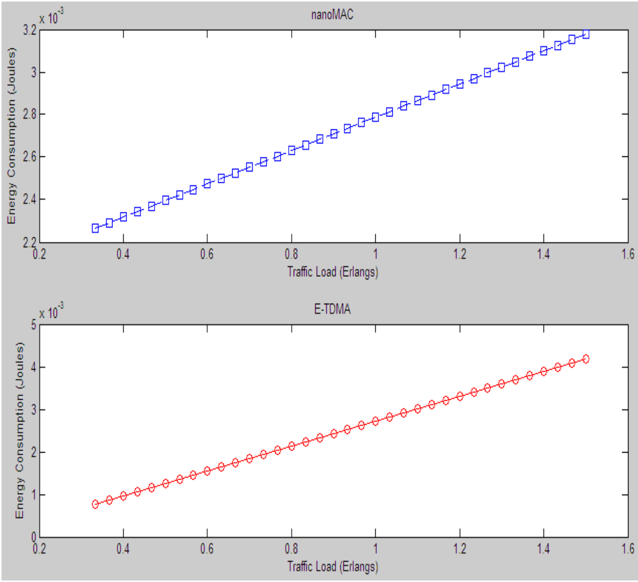

Fig.9: Comparison of intra-cluster energy consumed with traffic load

4. Intra-cluster average packet delay using NanoMAC Protocol

A comparison of normalized delay characteristics of NanoMAC and E-TDMA protocols are shown in Fig.10. In NanoMAC protocol an ACK frame for the same transmission period and retransmits only the lost/collided frame, thus the delay offered in the network is times less compared to E-TDMA. In NanoMAC protocol, the sensor node has greater possibility to sense the channel and transmit the frame, thus its delay incurred in transmission of data decreases.

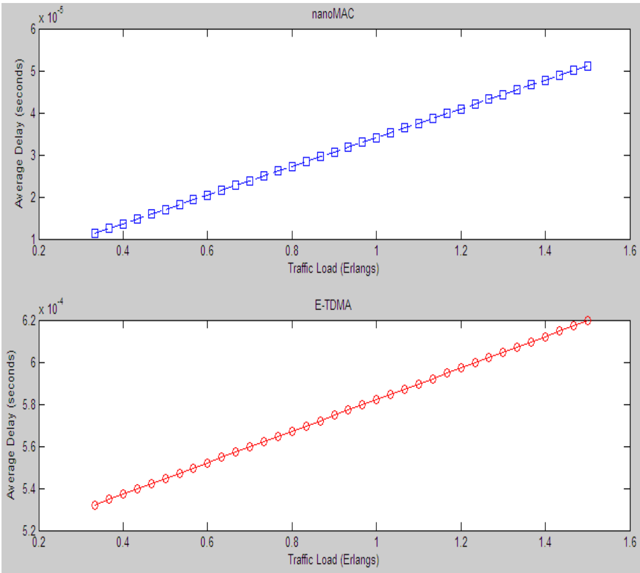

Fig. 10: Intra-cluster average packet delay

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VI. CONCLUSIONS

In this paper, the performance of the novel MAC protocol in terms of energy and delay with offered traffic load has been presented for the cluster based wireless sensor network. Simulation results shows that for the intra-cluster communication, BMA protocol performs best and achieves reduction in energy consumption compared to E-TDMA and provides less packet transmission delay by incorporating proper dynamic scheduling schemes. Also Nano MAC protocol provides better performance for inter-cluster communication and its energy expended for data transmission is less than E-TDMA protocol.

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