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Energy-Efficient MAC Protocols for Wireless Sensor Networks

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Abstract: **Due to advancement in the technology, Wireless sensor networks proves to be most promising technology for many application areas where the continuous real-time monitoring and sensing of various process parameters are the key objectives. But the low energy poses a great design challenge for WSN. Many energy-efficient solutions have been proposed by the researchers. Energy-efficient medium access control protocol is one of the solutions. This paper studies different MAC protocols such as TDMA, BMA and S-MAC. We analyze the energy models of these protocols and their performance of energy consumption is simulated with an NS-2 network simulator.**

Keywords: **- Wireless sensor networks, Energy Consumption, TDMA, BMA, S-MAC.**

I. INTRODUCTION

The rapid evolution of wireless technologies and the significant growth of wireless network services have made wireless communications an ubiquitous means for transporting information across many different domains. Within the framework of wireless Sensor Networks (WSNs), there are many potential possibilities where a WSN can be deployed to support numerous applications. Wireless Sensor Networks (WSNs) are ad-hoc networks, consisting of spatially distributed devices (motes) using sensor nodes to cooperatively monitor physical or environmental conditions at different locations. Devices in a WSN are resource constrained; they have low processing speed, storage capacity, and communication bandwidth. In most settings, the network must operate for long periods of time, but the nodes are battery powered, so the available energy resources limit their overall operation. To minimize energy consumption, most of the device components, including the radio, should be switched off most of the time [1]. Another important characteristic is that sensor nodes have significant processing capability in the ensemble, but not individually. Nodes have to organize themselves, ad-ministering and managing the network all together, and it is much harder than controlling individual devices. Furthermore, changes in the physical environment where a network is deployed make also nodes experience wide variations in connectivity and it influences the networking protocols. Medium access control (MAC) is used to avoid collisions by keeping two or more interfacing nodes from accessing the medium at the same moment. This is essential to the successful operation of shared-medium networks. As the sensor nodes have limited battery power, energy efficiency is the major concern in the design of wireless sensor networks [2].

Following are the primary attributes of WSN that must be consider during the design of the network.

•Energy Efficiency: One of the most important attribute as sensors with low power supply and usually deployed in adverse environment. Replacement of batteries is almost impossible.
•Scalability and Adaptively: Network Size, node density and topology changes should be acceptable.
•Latency: Time required transmitting the data packets from source to destination.
•Throughput: Number of data packets successfully transmitted by the sender to the receiver in unit time.
•Channel utilization: Also called bandwidth utilization or channel capacity show how effectively channel is utilized.
•Fairness: All sensor nodes should get equal chance to share the medium.

The main sources of energy dissipation in WSN are [3]:
•Collision: When two nodes transmit data packets at the same time.
•Overhearing: When the node receives the packets which are intended for some other node.
•Idle listening: It happens when node is waiting for data packets from other node.
•Over-emitting: Node transmits the data packet but the receiver is not ready to accept it.
•Control packet overhead: This is the energy required to handle control packets in the network.

MAC protocols are categorised into contention based, scheduled based and hybrid schemes. Contention-based protocols are scalable and adaptable to node density or traffic load variations. But these schemes are prone to more energy wastage due to collision, idle listening. Scheduled-based protocols are collision free so more energy efficient. But, they have limited flexibility and scalability [4].

This paper implements and investigates three MAC Protocols TDMA, BMA and SMAC. Also compares the performance of all protocols with different performance measures. This paper is organised as follows. Section II represents the review of existing literature. Working of mentioned protocols is described in section III. Analytical models for energy consumption of three protocols are specified in section IV and sections V evaluates the performance of all the protocols. Section VI concludes the paper with future scope.

II. RELATED WORK:

2.1 Scheduled-based MAC protocols-

Time-division multiple access (TDMA) is scheduled-based protocol in which the channel is divided into several time slots. Every node is allocated with a specific slot. Node is active only in its assigned slot, does the data transmission and turns to sleep state for all other time slots [3]. Conventional TDMA MAC protocols are collision free as node transmits data in fixed individual slots. It is also energy-efficient as all nodes are sleeping all the time except its transmission slot. TDMA is suitable for network with heavy traffic but it is in case of light or medium traffic where few nodes have data for transmission and other nodes those do not have data to send sit idle during its allocated time slot resulting wastage of energy in idle listening. Also CH has to keep its radioactive all the time to receive data caused energy dissipation in idle time. The Energy Adaptive TDMA(EA-TDMA) overcomes this energy dissipation due to idle listening by allowing sensor node to move in sleep state if it has no data to transmit in its allocated slot. Thus saves energy due to idle listening. But CH has to be active all the time [3].

TDMA protocol could be cluster based TDMA and distributed TDMA. In cluster based TDMA, nodes are organized into the different cluster each with cluster head. Cluster head decides the time slot for each node in the cluster. Distributed TDMA is more complex than cluster-TDMA because spatial reuse of a time slot could be possible. In this type, more than one node can communicate at the same time if their intended receivers are not interfering with each other.

The authors in [2] proposed a Bit-Map-Assisted Energy-Efficient MAC Scheme for Wireless Sensor Networks (BMA). BMA is a cluster-based protocol based on the working of traditional TDMA. It introduces a contention period at the beginning of each TDMA frame. In this phase, if a node wishes to transmit the data then it sends a 1-bit control message in its assigned slot to cluster head for the reservation of the data slot. In this way, cluster head has knowledge of how many source nodes are there in the current frame and CH accordingly prepares a schedule for data transmission. BMA introduces extra scheduled overheads as compared to TDMA. But, it shows poor channel utility for event-driven applications.

LMAC [5] is a distributed TDMA protocol in which time is divided into frames and slots. Each node has its own assigned slot. A slot is divided into control section and data section. When a node want to transmit data, it broadcasts a control message which includes the information about destination, data size, etc. until its time slots comes around. Then it transmits its data. The listening nodes turn its radio off during the data slot if they are not intended receiver of the message. One drawback of this protocol is, all the nodes always have to listen to the control messages of all slots in the frame even though the slots are unused.

TRAMA [6] is another distributed TDMA protocol in which time is divided into slots and each slots is divided into a random access interval and a data transmission interval. Nodes periodically broadcast its transmission schedule to its one-hop neighbours and thus learn about their two-hop neighbourhood. With this knowledge, nodes reserves future slots for backlogged traffic. There is assurance that only one node from two-hop neighbour transmits data in a given slot due to use of hash-based priority algorithm. Complex implementation of TRAMA protocol makes it difficult for the use in real time applications.

Y-MAC [7] is a TDMA-based multi-channel MAC protocol which is receiver centric energy-efficient for low traffic networks. It divides time into frames and slots like TDMA in which each frame contains a broadcast period and a unicast period. At the starting of a broadcast period every node is active and contends for medium access during this period. Each slot in unicast period is assigned to only one node for receiving the data. Contention between multiple senders is resolved in the contention window, which is at the beginning of each slot. Y-MAC uses slot assignments such as TDMA, but communication is receiver-driven to ensure low-energy consumption. It further uses multiple channels to increase the achievable throughput and reduce delivery latency. The main drawbacks of the Y-MAC approach are that it has the same flexibility and scalability issues as TDMA (i.e., fixed slot allocations) and that it requires sensor nodes with multiple radio channels.

2.2 Contention based MAC Protocols- SMAC [8] protocol is contention-based duty cycled protocol to reduce energy consumption provides good scalability and collision avoidance. Each node decides its own sleep/listen schedule and broadcasts it to its possible neighbors using SYNC message. Neighboring nodes either follows that schedule or may decide its own one. Contention for the medium is resolved by RTS/CTS mechanism.

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TMAC [9] is a variation to S-MAC in which it replaces fixed listening period of S-MAC by adjusting listening period according to traffic load. Nodes wake up at the beginning of a slot to listen very briefly for activity and if no activity is identified then node return to sleep state. Node remains awake for some time duration after completion of transmission if it observes more traffic thus eliminates early sleeping problem of S-MAC. T-MAC keeps intended receivers awake by sending message intimating future transmission results in idle listing and thereby energy wastage. TA-MAC [10] is another variation of S-MAC. The initial contention window is adjusted as per the current traffic situation which reduces the probability of collision in the network. TA-MAC is more energy efficient because the idle listening time during back-off procedure is minimized by using a fast back-of scheme. TA-MAC proves itself more energy-efficient with higher throughput during high traffic load.

III.ALGORITHM DESCRPTION

3.1Time Division Multiple Access (TDMA) [11]:
TDMA is a schedule-based MAC protocol where the transmission channel is divided into several time slots, and each node is assigned a time slot. Each node turns its radio on and does data transmission in its assigned slot only and for remaining slots node is in sleep mode to save energy [12]. However, this protocol is more energy efficient in high traffic load only because all nodes almost have the probability to send data. But in case of light traffic loads many node does not have data for transmission and they sits idle during their allocated time slots and thus energy is dissipated in idle listening.
A single round for TDMA protocol is shown in figure 1.

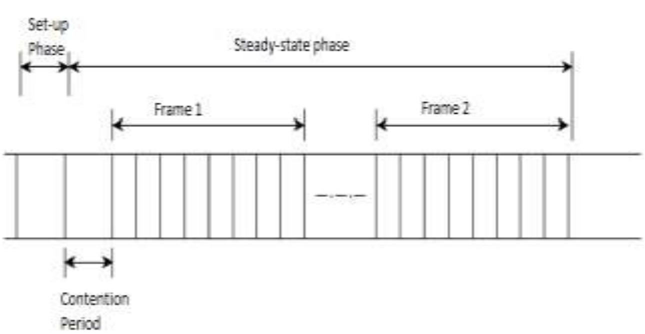

Fig. 1. Operation of TDMA protocol

3.2 Bit-Map Assisted Protocol (BMA): It is an event-driven protocol for intra-cluster communication. The main goal is to minimize energy consumption caused due to idle listening with minimum transmission delay. The operation of BMA is divided into rounds. Each round consists of two phases. First phase is set-up phase and second is steady-state phase.

Cluster Set-up phase : The entire wireless sensor network is divided into no of clusters in this phase. Among all the node, the node with highest energy is selected as a Cluster head (CH). Once CH is elected, it broadcasts the advertisement message informing all other node about its designation as CH using non-persistent CSMA. The remaining node joins the one of the cluster in which communication with CH requires minimum energy. Once the clusters are setup, the network enters into Steady-state phase.
Steady-State Phase: The Steady-state phase is divided into k sessions. Each session is of fixed duration and consists of contention period followed by a data transmission period or idle period. If there are N non-cluster head nodes then the contention period consists of N slots. As all the nodes does not have data to send in the current session, the data transmission period is variable. Here all the data slots are assumed to be of equal size. The number of data slots in each session depends on the amount of data to be transfer.
At the beginning of the contention period, all the nodes are in active state. Each node is assigned with specific slot by using TDMA protocol. If the node has data to transmit then it sends a 1-bit control message in its allocated slot to CH. Else it remains idle during its slot. A node is called as source node if it has data to transmit.
Once the above task is completed, a CH gets the complete information about how many nodes wishes to transmit the data in the current session and accordingly CH prepares the schedule for data transmission period. It broadcasts this schedule to all the nodes in the cluster. Now the system is in data transmission phase. If none of the nodes have data to transmit the network moves to idle period which ends up at the start of the next session.
In the data transmission period, each node transmits the data in its assigned slot to CH and turns its radio off after the completion of data transmission and also during all the other slots. The entire non-source node is in sleep mode during the entire session. After the end of current session, the next session begins with the contention period and the same procedure is repeated. CH collects the data from the source nodes. Data aggregation and compression is done at the CH locally and the data is forwarded to the base station. After a predefined time, the system starts with next round and the whole process is repeated.

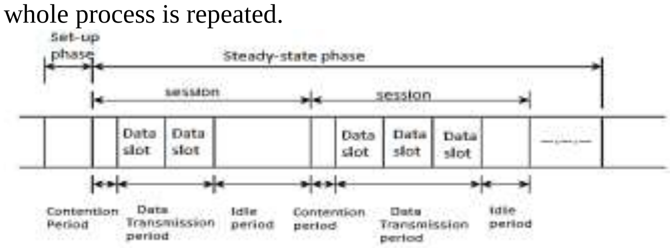

Fig. 2. Operation of BMA Protocol

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3.3 Sensor Medium Access Control Protocol(S-MAC):
S-MAC is a duty cycle approach protocol means node periodically does transition between a listening state and a sleeping state. Each node selects its own schedule of listen/sleep state and does synchonization with the other nodes to follow the same schedule. The nodes which follows the same schedule i.e. they listen or sleep at the same time forms a virtual cluster. No actual clustering takes place in the network and all the nodes are free to communicate wirh each other. SYNC message is used to exchange the schedule among the neighboring nodes. Thus each nodes has knowledge about listen/sleep timings of the neighbors. If node wants to transmit the data it first senses the medium using Reuest-to-send(RTS) and Clear-to-send(CTS) message between sender and reciever. To decide the schedule, a node first listen to the medium for a certain amount of time and if it receives a schdule from a nerighbor then it follows the same shedule. Otherwise, it prepares its own schdeule and broadcasts it to all the possible neighbors after a random delat td which reduces the collision possiblity due to multiple followers. Also nodes can adpot mulitple schdules. When node's own schedule is followed by other nerighboring nodes then the broadcasting node becomes synchronuzer node.
S-MAC divides a node's listen interval further into a a part for receiving SYNC packets and a part for receiveing RTS packets as sown in fig. 4.

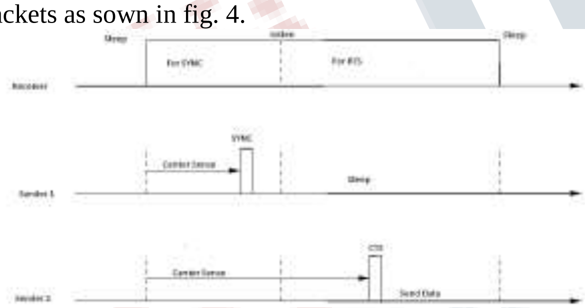

Fig. 3. Operation of S-MAC Protocol

Each slot is again futher divided into small slots for carrier sensing. A node wish to send SYNC or RTS packet randomly chooses a slot and senses the medium. If medium is free then it starts the transmission. Otherwise it moves to sleep state till the medium becomes free. The communication between sender and receiver is through exchange of RTS/CTS message for collision avoidance. Sleep and listen parameters are decided beforehand and may be inefficient for the actual traffic characteristics in the network.

IV. ANALYTICAL MODELING

This protocol is a cluster-based network in which one CH and N non-CH nodes. Assuming there are l frames in a round and n_k source node (source nodes which have data to send) in the k_{th} frame. The data slot duration is T_d. Let the node transmits the data with the probability p. T_d is the time required to transmit or receive a data packet and T_c is the time required to transmit or receive control packet. The time required for CH to transmit a control packet to all non CH nodes is $T_{ch.}$ The time required for a node to switch on , check its buffer and turn its radio off is T_e.
The parameters used in the analysis are defined in Table 1.

Variable	Meaning
N	Total number of normal nodes in a Cluster
P_t	Power consumption in transmit mode
P_r	Power consumption in reciever mode
P_e	Power consumption in empty-buffer mode
P_i	Power consumption in idle mode
T_d	Time required to transmit or receive a data packet
T_e	Time required to switch on,check, turn radio off
T_c	Time required transmit or receive a control packet
E_{cont}	Energy dissipated in a node in contention period
E_{frame}	Energy dissipated in node in frame transmission
E_{trans}	Energy dissipated in node in a transmission round.

4.1 Energy Consumption in TDMA Protocol:
During the contention period CH and non-CH nodes are active and data transmission is between CH and all non-CH nodes. CH assigns data slots to each node and broadcast this information to all nodes in the cluster. Therefore, energy required by CH to send a control message is $P_tT_{c,}$ and energy required by each node to receive a control message is $P_rT_{c,.}$ Therefore energy consumption in a contention period is given by

$$E_{cont} = NP_rT_c + P_tT_c \quad (1)$$

Each node transmits, at most, one packet per frame interval. Energy consumed by source node for data transmission is $P_tT_{d.}$ A non-source node is idle during its assigned slot so energy required by a non-source node is P_iT_d. A CH is also idle during the data slot of a non-source node, so energy consumed by CH is P_iT_d.
A node sends data with the probability p and remains idle with the probability (1-p) in its data slot. The expected energy consumption during a single frame a transmission with N data slot and l frames is as follows.

$$E_{trans} = [pP_tT_d + (1-p)P_iT_d + pP_rT_d + (1-p)P_iT_d]lN \quad (2)$$

The average energy consumption for TDMA protocol can be written as

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$$E_{TDMA} = [NP_rT_c + P_tT_c][pP_tT_d + 2(1-p)P_iT_d + pP_rT_d]lN \quad (3)$$

4.2 Energy Consumption in BMA Protocol:

During the contention period all the nodes are active and each node sends a 1-bit control message to CH in its slot and remains idle during (N – 1) slots. In data transmission phase all nodes transmits its data to CH as per the schedule. Thus energy requirement by a source node in a session is

$$E_{sn} = P_tT_c + (N-1)P_iT_c + P_rT_{ch} + P_tT_d \quad (4)$$

The energy consumption by a non-source node as it is idle in the contention period and in sleep mode in the data transmission period is given by

$$E_{in} = NP_iT_c + P_rT_{ch} \quad (5)$$

The energy consumption by CH during a session is

$$E_{ch} = n_i(P_rT_c + P_rT_d) + (N-n_i)P_iT_c + P_tT_{ch} \quad (6)$$

Therefore, the total energy consumption in each cluster during the i[th] session

$$E_{si} = n_iE_{sn} + (N-n_i)E_{in} + E_{ch} \quad (7)$$

The average energy consumption in each round is

$$E_{BMA} = E\left[\sum_{i=1}^{k} Esi\right] = k[n\,E_{sn} + (N-n)E_{in} + E_{ch} \quad (8)$$

V. PERFORMANCE ANALYSIS OF ENERGY CONSUMPTION BY TDMA, BMA AND S-MAC

In this section we analyze the performance of three protocols TDMA, BMA and S-MAC in terms of energy consumption. Here, the mean energy consumption of the aforementioned three WSNMAC protocols for two data transmission are calculated which is mentioned in the following table.

Table 1. Energy Consumption of TDMA, BMA, S-MAC Protocols.

Sr. No	No of Nodes	Energy Consumption in TDMA(mJ)	Energy Consumption in BMA(mJ)	Energy Consumption in SMAC(mJ)
1	30	46.613	19.045	17.616
2	40	27.922	12.515	9.749
3	50	20.306	9.378	8.991
4	60	23.06	7.505	7.278
5	70	16.35	8.122	7.89
6	80	13.695	5.208	5.341
7	90	12.09	4.765	4.489
8	100	15.865	4.835	4.75

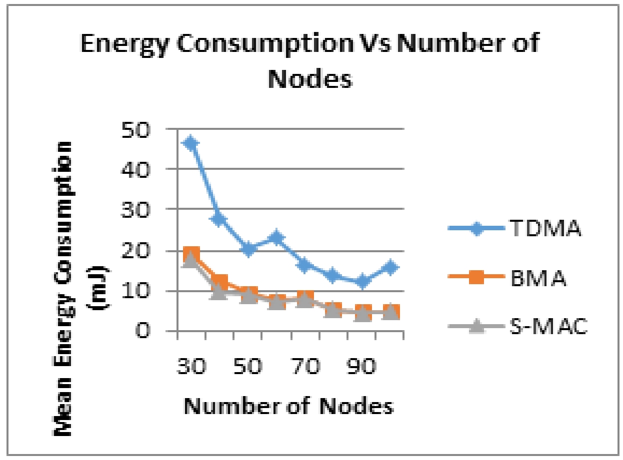

Fig. 5. Energy consumption of TDMA, BMA and S_MAC protocols as a function of number of nodes (N).

From the figure we can analyze that energy consumption of TDMA protocol is more as compared to BMA and S-MAC. Energy consumption of S-MAC is less than both TDMA and BMA. Thus S-MAC gives better results than TDMA and BMA.

V. CONCLUSION

When we compare the performance of TDMA, BMA and S-MAC protocol , then S-MAC shows better performance than TDMA and BMA. But this performance of protocols varies as the network conditions and parameters changes. In some situation like high traffic condition TDMA also gives good performance and at the same time S-MAC performance can be degraded due to collisions causes in high traffic conditions. BMA show good performance when network is event-driven.

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