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Bit-Map-Assisted Energy-Efficient MAC protocol for Wireless Sensor Networks

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Abstract

Time Division Multiple Access (TDMA) based Medium Access Control (MAC) protocols allocate one or more time slots to each sensor node. A node transmits its data during these slot(s) and keeps its radio OFF during all other slots. This inherently reduces idle listening, overhearing, and collision which are the major energy consuming factors. Some MAC protocols include a control period within each time frame. A node that has data for its Cluster Head (CH), books one or more slots by sending a data request (inside a control packet) during the control period. In response to the requests received, the CH sets up and broadcasts a schedule for the source nodes. Each source node transmits in its own slot(s) and keeps its radio OFF during the rest of the data transmission period. In the proposed MAC protocol named Bit-Map-Assisted Energy-Efficient MAC (BEE-MAC), the schedule is broadcasted only once in a round, and is followed throughout the duration of the round. This saves the energy which would have been consumed otherwise, in sending and receiving schedules, multiple times in a single round. The energy consumption in BEE-MAC is compared with the energy consumption in an existing MAC protocol. The results, which have been derived through mathematical calculations, show that BEE-MAC can save a considerable amount of energy by allowing the CH to broadcast the schedule only once in a round.

Keywords: *TDMA, radio, CH, control period, schedule, announcement period*

1. Introduction

A Wireless Sensor Network (WSN) is a collection of small autonomous devices which monitor their surroundings and cooperate with each other to forward the collected data to a Base Station (BS) [1, 2]. The BS is a device that connects the WSN to the outside world. The autonomous devices, also called sensor nodes, operate on batteries and communicate wirelessly. The battery is a very limited source of energy, and therefore should be used efficiently. Moreover, recharging or replacing the battery may not be easy, due to the climatic conditions and/or terrain features of the deployment area. The radio of a sensor node consumes the maximum amount of energy as compared to all its other components. The sensor node loses a considerable amount of energy even when its radio is ON, but neither transmitting nor receiving anything. This is called the IDLE state.

MAC protocols designed for WSNs, control when the radio is switched ON or OFF [3, 4]. An efficient MAC protocol can reduce the amount of time a node stays in the IDLE state. To this end, TDMA MAC protocols allocate one or more time slots to each sensor node in the network. Each node can transmit/receive to/from other nodes only during its own time slot(s). This inherently minimizes energy consuming factors like overhearing, idle listening and collision. Some MAC protocols partition the network into separate

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clusters, each having a Cluster Head (CH). The CH allocates slots to member nodes, collects data, aggregates it, and then forwards the aggregated data to the BS.

LEACH [5] allows each node to decide at the beginning of a round, whether it should elect itself CH for that round. BMA-MAC [6] and other related protocols follow the cluster formation procedure of LEACH. They introduce a control period in each frame. A member node which wants to send data in the current frame, has to book data slot(s) by sending a control packet in the control period. The CH sets up and broadcasts a schedule for those member nodes only. This avoids wastage of slots in the sense that only those nodes which book slot(s) are allocated the same. However, a lot of control packets may need to be exchanged during a frame to establish these slot assignments.

In this paper, we propose a TDMA based MAC protocol called Bit-Map Assisted Energy Efficient MAC (BEE-MAC). In this protocol the schedule is broadcasted only once in a round, and is followed throughout the duration of the round. As a result of this, the frame now contains only the control period and the data transmission period. By reducing the number of control packets that are exchanged during a frame, a reasonable amount of energy can be saved at the end of each round.

The rest of the paper is organized as follows. Section 2 briefly discusses some TDMA based MAC protocols that work towards energy conservation in WSNs. Section 3 explains the proposed TDMA MAC protocol in detail. Section 4 compares the proposed MAC protocol with an existing MAC protocol in terms of energy consumption. Finally, section 5 concludes the paper.

2. Related Work

This section discusses some TDMA MAC protocols that work towards energy conservation in WSNs. All the protocols discussed in this section divide the network into separate clusters. Each cluster is basically a group of sensor nodes in which one node is the CH. The function of the CH is to create and broadcast schedules for its cluster members, aggregate the data sent by them, and forward it to the BS. Clustering ensures that all the communications within a cluster are short range communications.

LEACH [5] proposed by Heinzelman *et al.*, in 2002, allows every node to decide at the beginning of a round, whether it should elect itself CH for that round. The decision is based on two factors: (a) the number of times the node has been cluster head and (b) node’s residual energy with respect to the aggregate energy remaining in the network. Each elected CH broadcasts an advertisement message that is heard by all the non-CH nodes that fall within its transmission range. A non-CH node decides to join one cluster, based on the received signal strengths of the advertisement messages. After the formation of clusters, each CH broadcasts a schedule in its cluster. A cluster member transmits data in its own slot and keeps its radio OFF in every other slot. After the CH has received data from all the members, it is aggregated and sent to the BS.

BMA-MAC [6] proposed by Jing Li *et al.*, in 2004, follows the same procedure as LEACH to create clusters in the network. But it includes an additional control period and announcement period in each frame. The control period consists of small control slots, each of which is allocated to one cluster member. A node which has some data for the CH, books a data slot by sending a control packet in its control slot. In the announcement period, the CH broadcasts a schedule for the source nodes. Each source node transmits in its own slot only and keeps its radio OFF for the rest of the data transmission period. During the idle period, all the source nodes and non-source nodes keep their radios OFF. Having collected data from all source nodes, CH aggregates it and sends it to the BS.

BMA-RR [7] proposed by Hsu *et al.*, in 2011, works almost in the same way as BMA-MAC. The difference however lies in the fact that each source node sends a request of the number of data slots that it needs. Allocation of data slots is done on a round-robin basis. Therefore, a node with multiple slots has to toggle its radio between ON and OFF numerous times during a frame. Furthermore, such nodes will have to wait longer for the completion of data transfer.

In BS-MAC [8] proposed by Alvi *et al.*, in 2015, the CH allocates short addresses of 1 byte each, to itself as well as all the member nodes. This is done during the cluster setup phase. These short addresses are used to exchange messages between the CH and the cluster members. A member may be allotted one or more slots to send/receive data to/from the CH. Allocation of slots is done on the basis of Shortest-Job-First algorithm.

BEST-MAC [9] proposed by Alvi *et al.*, in 2016, introduces a Contention Access Period (CAP) in each frame/session as shown in Figure 1 below. Nodes which could not join the network during the setup phase, send JOIN-REQ messages during this period. Such nodes are acknowledged instantly, but are notified about the allocated control slots only during the announcement period. A source node may be allocated one or more slots to send data to the CH. Slots are allocated using the Knapsack Optimization algorithm. It may so happen that there may not be sufficient number of data slots for a requesting node. In that case the available slots are allotted, and the node attempts to send the rest of the data in the next frame. However, this induces latency. Also there is no guarantee that the node will get the required number of slots in the next frame.

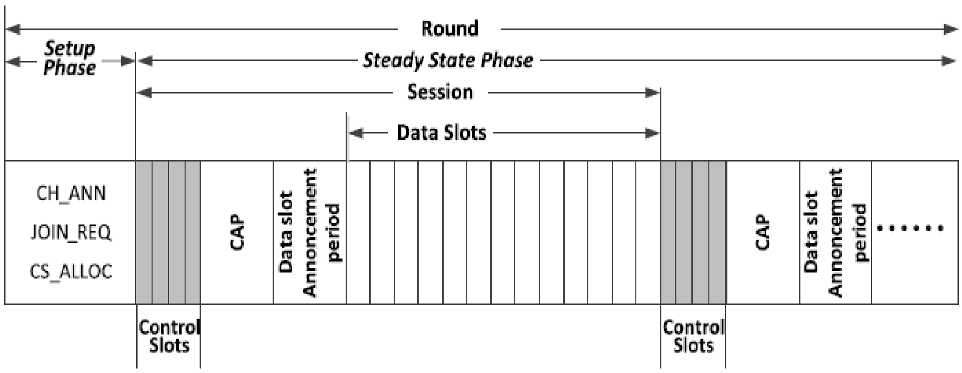

Figure 1. A Round in BEST-MAC [9]

In the protocol proposed in [10], the announcement phase features only once in a round. The schedule is announced before the commencement of the data transmission phase, and is followed throughout the duration of the round. Each frame contains only the control period and the data transmission period. The protocol was compared with BMA-MAC and was found to perform better than the latter in terms of energy conservation.

3. Proposed TDMA based MAC Protocol

The proposed TDMA MAC protocol divides the time in a round into three phases: Setup Phase, Announcement Phase and Data transmission phase, as shown in Figure 2. In the setup phase, the network is partitioned into separate clusters as in LEACH. In the announcement phase, the CH broadcasts a TDMA schedule in its cluster. The data transmission phase comprises *k* number of frames of equal length. Each frame consists of some control slots (in control period) and data slots (in data transmission period) as in [10]. The number of control slots is equal to the number of members in the cluster (excluding the CH). The number of data slots can be predefined to some value. A member which wants to book one or more data slots in the current frame, has to send a claim in the control slot allocated to it.

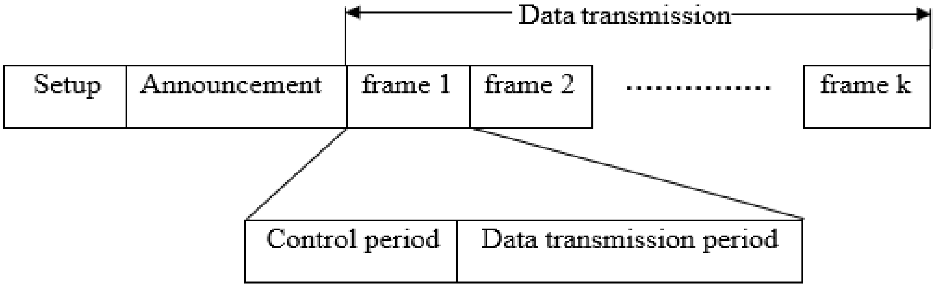

Figure 2. A Round in BEE-MAC

3.1. Setup Phase

The cluster formation process in the setup phase is same as that of LEACH. After CH election process, each elected CH will broadcast an advertisement message (ADV). This message may be heard by numerous non-CH nodes. A non-CH node may also receive multiple ADV messages if it lies within the transmission range of more than one CH. In such a case, the node decides to join the CH from which it has received the strongest signal. As in BEST-MAC, the CH allocates short addresses of 1 byte each, to itself as well as the members. These short addresses are used henceforth to communicate with the CH.

3.2. Announcement Phase

In this phase, the CH broadcasts a TDMA schedule in its cluster. This message contains the CH's extended and short address, each member node's extended and short address, start time of control period, control slot number allocated to each member, control slot duration, number of control slots, data slot duration, and number of data slots. The announcement phase features only once in each round unlike BEST-MAC. This saves the energy which would have been consumed otherwise, in broadcasting and receiving schedules, multiple times in a single round.

3.3. Data Transmission Phase

The data transmission phase consists of *k* number of frames of equal length. Each frame consists of a control period and a data transmission period. The control period consists of short control slots whereas the data transmission period consists of the longer data slots. CAP has been omitted from the frame structure. It may not be of any use after a few frames, because all the left-out nodes may have joined the network by then. A feasible solution is to increase the waiting time of the CH during the setup phase. Let us consider an example to understand the working better. A cluster consists of five member nodes, A, B, C, D, and E. A is allotted the first control slot, B is allotted the second control slot and so on. Figure 3 shows the structure of the first frame, based on the scenario which has been explained below.

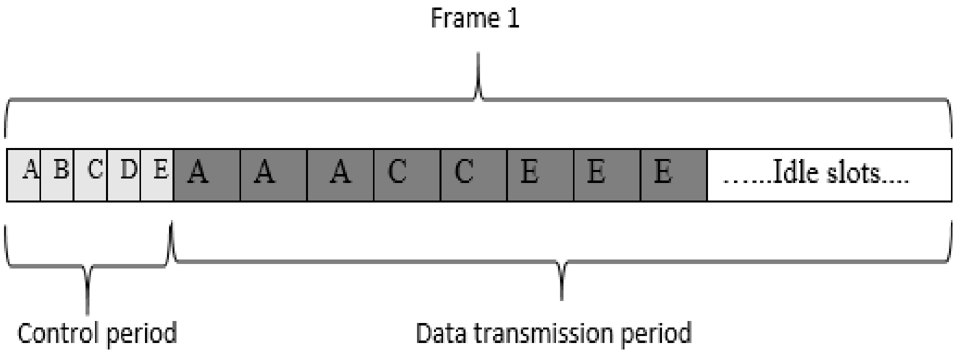

Figure 3. BEE-MAC Frame Structure

Member node A has some data for the CH. It turns its radio ON during its control slot and broadcasts a message claiming the first 3 data slots for itself. It has been assumed that nodes C and E have data for the CH as well. Therefore, they too have turned ON their radios at the beginning of control slot 1. The CH obviously has to keep its radio ON throughout the control period. So, the message broadcasted by node A is heard by CH, C, and E. The first 3 data slots are automatically allotted to A. CH, C, and E, all know that A will transmit in these slots. After broadcasting the message, A can turn OFF its radio for the rest of the control period.

Node B does not have any data for the CH, and therefore keeps its radio OFF during its control slot. CH, C, and E, all now know that B will not be using any data slots. Node C which has been listening till now, broadcasts a message in its control slot, claiming the next 2 data slots (slot 4 and slot 5) for itself. This is heard by CH and E. After broadcasting the message, node C can turn OFF its radio for the rest of the control period. Node D does not have any data for CH, and therefore keeps its radio OFF during its control slot. CH and E conclude that D won't be using any data slots. Node E which has been listening till now, claims the next 3 data slots (slots 6, 7, and 8) in its control slot. After broadcasting, E turns its radio OFF. From the messages received during the control period, the CH can safely infer that no one will be transmitting from 9^{th} slot onwards.

The messages transmitted during the data transmission period are unicast messages. All these messages are directed towards the CH. Node A turns its radio ON at the beginning of data slot 1, transmits for 3 consecutive slots (slots 1, 2, and 3), and goes into sleep state (radio OFF) after that. Node C turns its radio ON at the beginning of data slot 4, transmits during slots 4 and 5, and turns its radio OFF after that. Node E turns its radio ON at the beginning of data slot 6, transmits for 3 consecutive slots (slots 6, 7, and 8), and then returns to the sleep state. The CH is aware that no one will be transmitting from the 9^{th} slot onwards. These slots have been referred to as the idle slots, during which the CH too can turn OFF its radio to conserve energy.

When the CH has collected data from all the source nodes, it computes the aggregate and forwards it to the BS. After the completion of this frame, the next frame begins and the same procedure is repeated. To deal with the issue discussed in BEST-MAC, the data transmission period is predefined to contain y ($y = x \times$ number of member nodes) slots, and each node is allowed to transmit in a maximum of x consecutive slots. When the current round is over, the system begins the next round and all the phases discussed above are repeated.

4. Comparative Analysis

We compare the energy consumption in BEE-MAC with BEST-MAC to show that BEE-MAC is more energy efficient than BEST-MAC. It should be noted that only the energy consumed by the radio has been considered. Energy consumption by the sensor and the processor is much less to be considered.

4.1. Energy Consumption in BEST-MAC

The energy consumption in BEST-MAC has been divided into two stages: (a) energy consumed in the setup phase and (b) energy consumed in the steady state phase.

(a) ***Energy Consumed in the Setup Phase***

Total energy consumed by a CH during setup phase is:

$$E_{ch}^{SP} = E_{ch}^{SP-ADV} + E_{ch}^{SP-JR} + E_{ch}^{SP-SCH} + E_{ch}^{SP-idle} \quad (1)$$

- E_{ch}^{SP-ADV} is the energy consumed in transmitting the ADV message
- E_{ch}^{SP-JR} is the energy consumed in receiving JOIN-REQ messages
- E_{ch}^{SP-SCH} is the energy consumed in transmitting the schedule for control slots
- $E_{ch}^{SP-idle}$ is the energy consumed when the CH is idle (the radio is continuously ON to receive JOIN-REQ messages, some of the time is spent in idle listening)

Total energy consumed by n member nodes during setup phase is:

$$E_{mn}^{SP} = (E_{mn}^{SP-ADV} + E_{mn}^{SP-JR} + E_{mn}^{SP-SCH} + E_{mn}^{SP-idle}) * n \quad (2)$$

- E_{mn}^{SP-ADV} is the energy consumed by a member node in receiving the ADV message
- E_{mn}^{SP-JR} is the energy consumed by a member node in transmitting JOIN-REQ message
- E_{mn}^{SP-SCH} is the energy consumed by a member node in receiving the schedule
- $E_{mn}^{SP-idle}$ is the energy consumed by a member node when it is idle (Some time may be spent in idle listening when the node is waiting for ADV message)

Total energy consumption in the cluster during the setup phase is:

$$E_{BEST-MAC}^{SP} = E_{ch}^{SP} + E_{mn}^{SP} \quad (3)$$

(b) ***Energy Consumed in the Steady State Phase***

Total energy consumed by the CH during one session of steady state phase is:

$$E_{ch}^{SSP} = E_{ch}^{CP-dreq} + E_{ch}^{CP-idle} + E_{ch}^{CAP-JR} + E_{ch}^{CAP-ACK} + E_{ch}^{CAP-idle} + E_{ch}^{AP-SCH} + E_{ch}^{DP-data} + E_{ch}^{DP-idle} \quad (4)$$

- $E_{ch}^{CP-dreq}$ is the energy consumed in receiving the data requests during the control period
- $E_{ch}^{CP-idle}$ is the energy consumed when the CH is idle during control period
- E_{ch}^{CAP-JR} is the energy consumed in receiving the JOIN-REQ messages during CAP

- $E_{ch}^{CAP-ACK}$ is the energy consumed in sending the acknowledgements during CAP
- $E_{ch}^{CAP-idle}$ is the energy consumed when the CH is idle during CAP
- E_{ch}^{AP-SCH} is the energy consumed in transmitting the schedule for data slots and control slots (newly joined nodes) during announcement period
- $E_{ch}^{DP-data}$ is the energy consumed in receiving data packets during data transmission period
- $E_{ch}^{DP-idle}$ is the energy consumed when CH is idle during data transmission period

Average number of source nodes per session is *m*. Total energy consumed by *m* source nodes (supposing that each source node is successfully allocated slots) during one session of steady state phase is:

$$E_{sn}^{SSP} = \left(E_{sn}^{CP-dreq} + E_{sn}^{AP-SCH} + E_{sn}^{DP-data}\right) * m \quad (5)$$

- $E_{sn}^{CP-dreq}$ is the energy consumed by a source node in transmitting the data request during control period
- E_{sn}^{AP-SCH} is the energy consumed by a source node in receiving the schedule during the announcement period
- $E_{sn}^{DP-data}$ is the energy consumed by a source node in sending data packets during the data transmission period

Average number of non-member nodes per session is *p*. Total energy consumed by *p* non-member nodes during one session of steady state phase is:

$$E_{nm}^{SSP} = \left(E_{nm}^{CAP-JR} + E_{nm}^{CAP-ACK} + E_{nm}^{CAP-idle}\right) * p \quad (6)$$

- E_{nm}^{CAP-JR} is the energy consumed by a non-member node in transmitting JOIN-REQ message to CH during CAP
- $E_{nm}^{CAP-ACK}$ is the energy consumed by a non-member node in receiving ACK from CH during CAP
- $E_{nm}^{CAP-idle}$ is the energy consumed when a non-member node is idle during CAP (sometime may be spent in idle listening when a non-member node is waiting for the ACK)

Total energy consumption in the cluster during k sessions of steady state phase is:

$$E_{BEST-MAC}^{SSP} = (E_{ch}^{SSP} + E_{sn}^{SSP} + E_{nm}^{SSP}) * k \quad (7)$$

Total energy consumed in the cluster during one round of BEST-MAC is:

$$E^{BEST-MAC} = E_{BEST-MAC}^{SP} + E_{BEST-MAC}^{SSP} \quad (8)$$

4.2. Energy Consumption in BEE-MAC

The energy consumption in BEE-MAC has been divided into three stages: (a) energy consumed in setup phase, (b) energy consumed in announcement phase, and (c) energy consumed in data transmission phase.

(a) ***Energy consumed in the setup phase***

Total energy consumed by a CH during setup phase is:

$$E_{ch}^{SP} = E_{ch}^{SP-ADV} + E_{ch}^{SP-JR} + E_{ch}^{SP-idle} \quad (9)$$

- E_{ch}^{SP-ADV} is the energy consumed in transmitting the ADV message
- E_{ch}^{SP-JR} is the energy consumed in receiving JOIN-REQ messages
- $E_{ch}^{SP-idle}$ is the energy consumed when the CH is idle (the radio is continuously ON to receive JOIN-REQ messages, some of the time is spent in idle listening)

Total energy consumed by n member nodes during setup phase is:

$$E_{mn}^{SP} = (E_{mn}^{SP-ADV} + E_{mn}^{SP-JR} + E_{mn}^{SP-idle}) * n \quad (10)$$

- E_{mn}^{SP-ADV} is the energy consumed by a member node in receiving the ADV message
- E_{mn}^{SP-JR} is the energy consumed by a member node in transmitting JOIN-REQ message
- $E_{mn}^{SP-idle}$ is the energy consumed by a member node when it is idle (Some time may be spent in idle listening when the node is waiting for ADV message)

Total energy consumption in the cluster during the setup phase is:

$$E_{BEE-MAC}^{SP} = E_{ch}^{SP} + E_{mn}^{SP} \quad (11)$$

(b) ***Energy consumed in the announcement phase***

Total energy consumed by the CH during announcement phase is:

$$E_{ch}^{AT} = E_{ch}^{AP-SCH} \quad (12)$$

- E_{ch}^{AP-SCH} is the energy consumed by the CH in transmitting the schedule for control slots and data slots during the announcement period

Total energy consumed by n member nodes during announcement phase is:

$$E_{mn}^{AT} = (E_{mn}^{AP-SCH}) * n \quad (13)$$

- E_{mn}^{AP-SCH} is the energy consumed by a member node in receiving the schedule during the announcement period

Total energy consumption in the cluster during the announcement phase is:

$$E_{BEE-MAC}^{AT} = E_{ch}^{AT} + E_{mn}^{AT} \quad (14)$$

(c) ***Energy consumed in the data transmission phase***

Total energy consumed by the CH during one frame of data transmission phase is:

$$E_{ch}^{DT} = E_{ch}^{CP-dclm} + E_{ch}^{CP-idle} + E_{ch}^{DP-data} \quad (15)$$

- $E_{ch}^{CP-dclm}$ is the energy consumed by the CH in receiving claims for data slots during the control period
- $E_{ch}^{CP-idle}$ is the energy consumed by the CH when it is idle during the control period (some time is spent in idle listening when the CH is waiting for data slot claims)
- $E_{ch}^{DP-data}$ is the energy consumed by the CH in receiving data packets during the data transmission period

Average number of source nodes per frame is m. Total energy consumed by m source nodes during one frame of data transmission phase is:

$$E_{sn}^{DT} = (E_{sn}^{CP-rclm} + E_{sn}^{CP-idle} + E_{sn}^{CP-dclm} + E_{sn}^{DP-data}) * m \qquad (16)$$

- $E_{sn}^{CP-rclm}$ is the energy consumed by a source node in receiving the claims of other source nodes during the control period
- $E_{sn}^{CP-idle}$ is the energy consumed by a source node when it is idle during the control period (waiting to receive claims of other source nodes)
- $E_{sn}^{CP-dclm}$ is the energy consumed by a source node in sending its claim to the CH during the control period
- $E_{sn}^{DP-data}$ is the energy consumed by a source node in sending the data to the CH in the data transmission period

Total energy consumption in the cluster during k frames of data transmission phase is:

$$E_{BEE-MAC}^{DT} = (E_{ch}^{DT} + E_{sn}^{DT}) * k \qquad (17)$$

Total energy consumed in the cluster during one round of BEE-MAC is:

$$E^{BEE-MAC} = E_{BEE-MAC}^{SP} + E_{BEE-MAC}^{AT} + E_{BEE-MAC}^{DT} \qquad (18)$$

4.3. Comparison between BEE-MAC and BEST-MAC

Based on the equations depicting the energy consumption, the following points can be concluded.

(a) ***Energy consumed in setup phase***

During the setup phase, E_{ch}^{SP-SCH} is the energy saved by a CH in BEE-MAC. Similarly each member node saves E_{mn}^{SP-SCH} energy during the setup phase of BEE-MAC. Therefore, the energy consumed in the setup phase of BEE-MAC is less than the energy consumed during the setup phase of BEST-MAC.

$$E_{BEE-MAC}^{SP} < E_{BEST-MAC}^{SP}$$

(b) ***Energy consumed in k sessions/frames***

During each frame of BEE-MAC, a CH saves $E_{ch}^{CAP-JR} + E_{ch}^{CAP-ACK} + E_{ch}^{CAP-idle} + E_{ch}^{AP-SCH} + E_{ch}^{DP-idle}$ energy. There is also an added energy overhead of E_{nm}^{SSP} in each session of BEST-MAC. For some frames, $E_{sn}^{DT} > E_{sn}^{SSP}$, as $E_{sn}^{CP-rclm} + E_{sn}^{CP-idle}$ energy will also add to the energy consumption by one or more source nodes. However, considering the energy that is saved in each frame of BEE-MAC, it can be inferred that BEE-MAC saves more energy than BEST-MAC in k sessions/frames.

$$E_{BEE-MAC}^{DT} < E_{BEST-MAC}^{SSP}$$

(c) ***Energy Consumed in a Round***

There is one extra phase in BEE-MAC called the announcement phase, in which $E_{BEE-MAC}^{AT}$ energy is consumed. In BEE-MAC, the schedule for control slots and data slots is transmitted in the same message, and just once in a round. In BEST-MAC, a schedule for data slots is transmitted in every session. Moreover, the schedule may carry information about control slots allocated to the newly joined members. Hence, the induction of a separate announcement phase is rather advantageous for BEE-MAC. It can now be concluded from (a), (b), and (c) that BEE-MAC saves more energy in a round than BEST-MAC.

$$E^{BEE-MAC} < E^{BEST-MAC}$$

5. Conclusion

In this paper, we have proposed a TDMA based MAC protocol named BEE-MAC which is aimed at reducing the energy consumption in sensor nodes. In BEE-MAC, the announcement phase features only once in each round. This saves the energy which would be consumed otherwise, in transmitting and receiving schedules, multiple times in a single round. Each source node can claim one/more slots for itself, based on the information that how many slots have already been claimed by other source nodes. As the CH listens to all the data slot claims, it knows that how many slots will remain unused. So, the CH can turn OFF its own radio during those slots to conserve energy. The energy consumption in BEE-MAC has been compared with that of BEST-MAC. On the basis of the calculations involving energy consumption, it has been shown that the total energy consumed in one round of BEE-MAC is less than that of BEST-MAC. BEE-MAC will also perform better in terms of energy consumption, when compared to other protocols like BEST-MAC.

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