Novel Energy Efficient MAC Protocol for Data Collection in Event Based Wireless Sensor Network

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Abstract*— In this paper we propose an energy efficient Aggregation Node selection for event data collection and a novel MAC protocol. We have integrated these two algorithms in wireless sensor network to extend the lifetime of the network. Our protocol is designed for event-driven and low power embedded sensor networks. Idle listening for radio traffic is more expensive compared to sending the sensed data in wireless sensor network. In an event driven sensor network multiple sensors may detect the same event and all of them contend for medium access to transmit the data, and it may lead to network congestion and retransmission of a packet. Our proposed wireless sensor network selects the Aggregation Node to collect the event data from all the event affected nodes. Aggregation Node computes the energy efficient wakeup schedule of event affected nodes to shorten the idle listening, to avoid the control packet overhead and to cut down the energy wastage. Segment the data into smaller packets to reduce the cost of retransmission. After receiving the message the routing algorithm will identify the next node based on the sleep schedule and residual energy to transmit the message and proposed MAC contends to access the medium. Simulation results shows that, our combined routing and energy efficient MAC protocol for event-driven wireless sensor network concedes higher efficiency and reduce the latency than existing approaches.

Keywords — Adaptive sleeping, event-driven, routing, MAC, aggregation

I. INTRODUCTION

Recent progress in research and development of micro-machined devices and ultra low power wireless communication indicates the future for wireless sensor network(WSN) . The technological developments have made sensors more practical for capturing domain specific events. Most important function of wireless sensor network is to monitor the human inaccessible areas such as volcano monitoring, underwater, robotic spacecraft monitoring and other similar applications. In many wireless sensor network applications, a large number of low-cost battery operated sensor nodes with limited computation (CPU), communication (radio unit) and storage (memory) have been deployed to monitor the harsh environment. The replacement of the batteries of such nodes in a grievous environment is difficult and even impossible [1][2]. On account of the limited battery capacities of the sensor nodes, minimizing the energy consumption is a crucial objective for all WSN. For the delay-sensitive applications (such as intrusion detection, fire hazards) the minimization of the communication delay is another critical objective [2].

In Sensor network, sensors are designed to sense the data and process it internally before communicating to the next node or sink. Sensors are deployed to monitor the physical phenomena of the desired area of interest and for specific application requirement. Some monitoring applications are continuously monitoring the data but in many such sensor networks, data generation rate is low and therefore results in long idle periods. Also, some sensor networks (e.g. for monitoring applications) are event based; when the desired event of interest occurs, high data rates are needed. Overall these application characteristics result in intermittent traffic [6]. As shown in the Figure 1 the WSN consists of sensor nodes. In some applications, these sensor nodes counts from few to several hundreds or even thousands, where each node is connected to one or sometimes several sensor nodes. Each such sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and power source, usually a battery or an embedded form of energy harvesting. A sensor node might vary in size due to recent development in MEMS technology and its size from that of a shoebox down to the size of a grain of dust. The cost of sensor nodes is similarly variable, ranging from a few to hundreds of dollars, depending on the complexity of the individual sensor nodes. Size and cost constraints on sensor nodes results in corresponding constraints on resources such as energy, memory, computational speed, and communications bandwidth. The topology of the WSNs can vary from a simple star network to an advanced multi-hop wireless mesh network. The propagation technique between the hops of the network can be routing or flooding.

Sensor nodes sense the data and transmit the same to the base station using single hop or multi hop routing. The base station is usually having the high power data processing and perform communication and it makes the decision based the sensor data. The sensor data can be accessed by the control points and authenticated control point device can send the http request to the base station or an individual sensor node using internet. The control point devices such as personal computer, PDA or smart phones have been used for sensor network management and also to update the sensor software to resolve the post deployment issues.

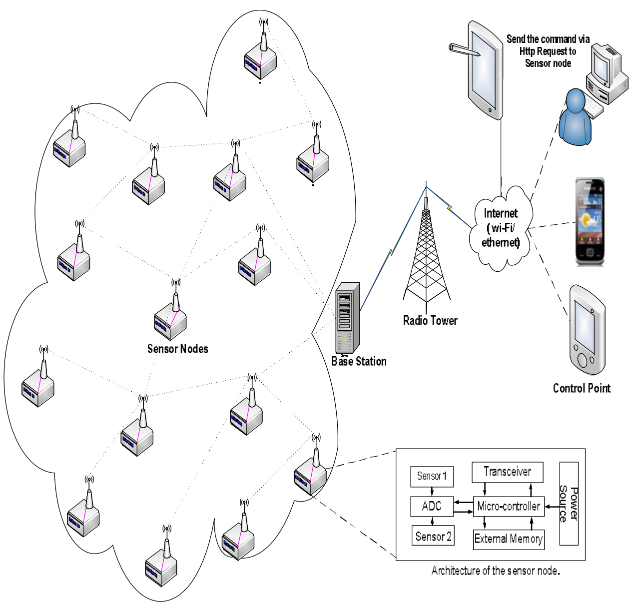

Figure 1 Typical Infrastructure of wireless sensor networks

The power-sink embedded hardware components usually have various modes of operation including low-power or sleep modes which can be used to minimize the power drain whenever the hardware components or software services related to them are not in use. The radio unit of sensor node is usually the most power-consuming hardware component. The radio transceiver often uses ten times much power compared to the power consumption of the CPU/microcontroller. Many energy efficient MAC protocol have been proposed for WSN to save the battery power by placing the radio in low-power modes when not actively sending or receiving data. Sleep mode is used to prolong network lifetime to match the query of long-time monitoring [4], and the design of sleep mode is a remarkable issue in WSN [3].

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A. Wireless Sensor Network MAC protocol

The main functionality of the MAC protocol is to streamline the usage of the medium and control the shared medium and wireless bandwidth. It can be done using channel access mechanisms. The channel access mechanism is the nitty-gritty of the MAC protocol. There are three main classes of channel access mechanisms for traditional wireless network's MAC protocols such as TDMA, CSMA and polling. Sensor network's MAC protocols differ greatly from traditional wireless network's MAC protocols in many challenging issues. Wireless sensor networks (WSNs) are usually battery powered, used to monitor the human inaccessible area and to make applications economically feasible. Such networks have to operate for a long period of time without recharging or replacing batteries. It has tremendous requirement to develop power aware techniques in all the layers of WSN that prolong the battery lifetime as much as possible. There are four major challenges in design of energy efficient MAC protocol, as lots of energy wastage happens due to idle listening, packet collision, overhearing and control packet overhead.

Many MAC protocols have been designed for WSN and they use the various energy efficient algorithm to save the battery power by placing the radio in low-power modes when not actively sending or receiving data. Wireless sensor hardware is generally cheap and designed with multiple power saving modes to extend the battery life of the sensor node. The Texas Instruments MSP430F20xx family microcontroller and RFM TR1001, hybrid transceiver (868.35 MHz) have been designed with multiple power saving modes, Table 1 provides a power breakdown of the processor and radio for active and sleep modes. Energy efficient MAC has been proposed to utilize the hardware capability to the full extent to prolong network lifetime. Table 1 indicates the importance of maximizing a node's sleep ratio because the node's transmitting and receiving power can go up to three times greater than the node's sleeping power.

Table -1 Power breakdown of Microcontroller and Radio Transceiver

CPU	
Active	220µA(1 MHz, 2.2 V)
Sleep	0.5µA
Off Mode(RAM Retention)	0.1 µA
Radio	
Transmit	10mA
Receive	04mA
Sleep	20 µA

The sleep ratio(R_s) of a sensor node has been calculated using the equation 1

$$R_s = \frac{Ts}{(Ta+Ts)} \quad \text{--------} \ (1)$$

Where T_a and T_s are active and sleep time
Lifetime of the sensor node (T_{lt}) has been calculated based on the sleep ratio and power consumption of active and sleep duty cycle of the node.

$T_{lt} = P_{battery}(mWh)\ (R_s)(P_s(mW)) + (1-R_s)\ (P_a(mW))$ --(2)

Where $P_{battery}$ is total available energy of the battery, R_s is sleep ratio, P_a and P_s are active and sleep mode power consumption. For both radio and CPU power consumption in active (P_a) mode is far more compared to power consumption in sleep mode (P_s). This indicates the importance of enhancing the node's sleep ratio. The power consumption of transmit, receive and CPU active duty cycle are in higher side of power consumption and it reduces the lifetime of the network. In our proposed system, on occurrence of the event the group of nodes will adaptively select the Aggregation Node for data collection; from here onwards it's called as AggNode. The AggNode decides the priority and active/sleep schedule of the event affected nodes based on their residual energy and distance to aggregation node for sending their event data to AggNode. The AggNode broadcasts the priority of the nodes, active and sleep schedule information of all the event affected sensor nodes. The highest priority node initiates the data transfer and rest of the nodes turns to sleep state till they get their turn for data transfer.

It is extremely difficult to guarantee continuous and reliable activity detection in wireless sensor network (WSN) applications. A major challenge with activity detection is that there are numerous sensors which are likely to move or exhibit failures due to hardware degradation, inaccurate readings, and environmental changes [7]. In many applications, far more sensor nodes are deployed than are actually needed to accurately sense the target phenomena. There are several reasons for the over deployment to ensure that even if nodes are randomly distributed, there is a high probability that at least a node present in a desired location to provide backup nodes in case of failure or battery depletion; or to have extra nodes available if more thorough data gathering is required[8].

The Medium Access Control (MAC) protocol directly controls the communication module, so it has important effect on the nodes' energy consumption. The major sources of energy inefficiency in WSN are collision, overhearing, idle listening, and control packet overheads. According to the four sources of energy wastage, researchers have proposed different types of MAC protocols to improve energy consumptions so that the WSN can have a long lifetime. Lowering down the duty cycle in favour of energy consumption leads to higher latency, which makes it unsuitable for many applications [6].

II. RELATED WORK

In recent fast, many researchers have been focused to design an energy efficient medium access control (MAC) protocols for event based wireless sensor network to reduce the power consumption. The available MAC protocols are classified as schedule-based such as time division multiple access(TDMA)[1][17] and contention based such as S-MAC[6], T-MAC[6] and PMAC[15]. TDMA protocols are better suited where in cluster head (CH) or base station directly communicates to the nodes in the WSN and assigns the fixed time slot for duty cycle and sleep schedule. In this protocol nodes will transmit the data only in assigned time slot and it helps in implementing the collision free wireless sensor network[1]. In low traffic applications TDMA protocols have underutilized the slots as there is not much data to transmit and also not easy to change the slot assignments dynamically, it may lead to idle listening for the remaining period[16].

S-MAC and T-MAC are contention based protocols and are inspired by the 802.11 MAC. S-MAC uses RTS/ CTS/DATA/ACK control packets to transmit packets in order to reduce collisions and overhearing by putting irrelevant nodes after receiving RTS/CTS packets to sleep. In S-MAC active and sleep time are fixed as shown in the Figure 2, when the load is lower than the active time slot, it's not optimally used and energy will be wasted on idle listening[16]. T-MAC active time is not fixed as showed in the Figure 3, and it depends mainly on the message rate: it can be so small that nodes are able to transfer all their messages within the active time. Every node periodically wakes up to communicate with its neighbours, and then go to sleep again until the next frame. New messages are queued when the intended node is not in active mode. T-MAC improves on S-MAC by reducing the idle time spent using a timeout scheme [18].

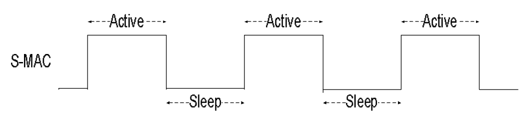

Figure 2 S-MAC duty cycle with fixed active time

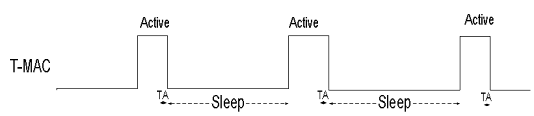

Figure 3 T-MAC duty cycle with adaptive active time

Sift MAC[14], EB-MAC [18] protocols are presented for event driven wireless sensor network , PMAC[15] is another protocol for sensor networks that adaptively determines the sleep-wake up schedules for a node based on its own traffic, and the traffic patterns of its neighbours. The node can put itself on long sleep for several time frames when there is no traffic in the network, so it can achieve a better throughput at high loads, and conserve more energy at light loads than SMAC. The invitation based MAC protocol has been proposed in [9] and its tree like parent –child structure which enables parent to send the invitation to multiple child node to send their data. The protocol PD-MAC[10] is improved version of S-MAC. Another S-MAC based protocol is EX-MAC[11] which coordinates the transfer of packets from source to destination to reduce the latency and jitter.

Many research works have been designed using MAC for event driven WSN applications in which sensor nodes transmit data only when they observe significant/predefined events. Bit-map assisted (BMA) is schedule-based and it's an appropriate protocol for low traffic conditions since it delivers better performance than TDMA and E-TDMA for low and medium traffic loads [1]. Sensor nodes changes their sleep schedule based on the traffic[12] to improve the throughput of the network. STC-MAC[13] protocol has mingled the CSMA and TDMA protocols to avoid the collision and crosstalk to achieve low latency.

III. Proposed Design

A. Problem Statement

In an event driven wireless sensor network sensors are competing for the medium only when an event occurs. In most sensor networks, multiple sensors are deployed to monitor the desired area. Usually sensors are densely deployed in an inaccessible environments, where maintenance would be inconvenient or impossible. In addition to sending periodic observations, when an event of interest happens, nodes covering the event affected area observe the event and report the event to sink . If multiple nodes pick the same shared medium to transmit at the same time and it leads to a network congestion, collision at receiver end; which ends up in lots of energy wastage.

B. System Design

Adaptive computing of a node for data aggregation and access control of shared medium is the main focus in this work. Concurrent access of the shared medium by multiple sensor nodes would lead to collision and retransmission of data packets resulting in degradation of the network efficiency and waste of energy in sensor nodes. Access control is a protocol by which decision is made as to who will access the medium at a given point of time. Another important function handled by the data link layer is flow control. The sender and the receiver come to an understanding on how much of data can be sent, so that it is convenient for both the sender and the receiver to optimize the bandwidth utilization, this function is called flow control. Our proposed system has been classified into three phases based on the functionalities such as initialization, data collection and communication phases. The data collection and communication of an event-driven system as shown in the Figure – 5.

Initial phase

1. Initially all nodes are location aware and know their distance from the sink
2. On initialisation every sensor node broadcasts a control message (Beacon_Msg) which includes source ID, residual energy R_E and radius r.
3. On receiving each node creates a neighbourhood table and updates distance d from the neighbour node and residual energy R_E

Data Collection Phase

1. On an event occurrence, event effected neighbouring nodes select the aggregation node(AggNode) as shown in Figure 6 (Select_AggregationNode)
2. The selected AggNode will broadcast its ID and R_E to neighbour nodes
3. The neighbour nodes accepts, updates its table and send the size of the sensed data to AggNode.
4. Depending upon the size of the sensed data and time required to send it to the AggNode, the AggNode compute the PriorityNode and decides the wakeup schedule of the event affected nodes and broadcasts the same .(AggNode is ready to receive as shown in fig)
5. On receiving, the respective node will wake up and start sending the sensed data and remaining nodes will sleep for designated time.

Communication phase

1. The AggNode starts two threads, One to compute the data aggregation and creates the smaller packets which is having source ID , destination Id and payload.
2. Another thread for communicating the data, which sends an RTS request to NearestNode and wait for CTS
3. Selects the NearestNode if d(AggNode, SinkNode) > d(NearestNode, SinkNode)
4. If (CTS received) then starts sending the data packets
5. Else
6. The AggNode does computation for the Alternate Nearest Node, sends an RTS request to AltNearestNode and waits for CTS
7. Selects the Alternate nearest node if d(AggNode, SinkNode) > d(AltNearestNode, SinkNode)
8. If(CTS received) then starts sending the data packets.

Figure - 4 Pseduo-code of Proposed System

In the initialization phase, nodes in the network introduce themselves by broadcasting the Beacon_Msg which contains the source Id, location info, residual energy and sleep schedule information to immediate neighbors which are within the communication radius. Then each neighboring node, by receiving the information, will construct the neighbor node table as shown in the Table - 2 which is utilized for the selection of Aggregation Node(AggNode) and selection of shortest routing path to perform the load balancing. The details of AggNode selection and event data collection is explained in next section. The MAC protocol uses the sleep schedule information to control the medium access and reduce the energy wastage. The energy efficient design and implementation of MAC protocol depends on the capabilities and features of the underlying radio transceiver and microcontroller. Our MAC protocol uses the power of in-network data processing and communication tasks simultaneously to determine the total energy required to transmit the amount of sensed data. In-network data processing greatly reduce the energy consumption compared to transmitting all the raw data to the end node[5].

Proposed system integrates the shortest path routing algorithm and stores the routing table and uses the two best shortest paths to route the control message and payload transmission. If the first shortest route is not feasible due to active/sleep duty cycle then it selects the second best shortest path until the first best route is available. As shown in Figure-5 the wireless sensor network with two events, E1 and E2 occurs in two different locations. When an event occurs one after the other then there is a less possibility of network congestion. In case of simultaneous occurrence of E1 and E2 , then both the AggNode contending for D1, which is at shortest distance. And thus it leads to collision at node D1.

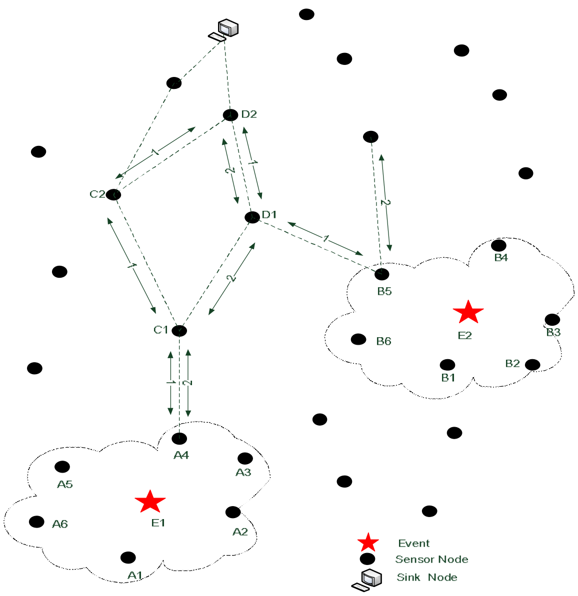

Figure 5. An Events has occurred in the sensor network

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In this scenario, one of these two AggNode has to wait for complete transmission of data. And it may lead to increase in latency and direct the waiting node into idle listening. Our proposed MAC protocol contending for shortest path as specified in the Figure - 4 : if the shortest node is busy in another data transmission, then AggNode of E1 selects the alternative shortest node C1 for forwarding the data. AggNode which selects the shortest path for forwarding the data packet consumes minimum energy and gives the high probability of successful delivery ratio. Since E1 selects the alternate shortest path it consumes more energy than first best shortest path but it reduces the delay in forwarding the event data to sink. It's very crucial in delay-sensitive applications such as fire accident monitoring and intrusion detection systems where freshness of the data is more important.

```
Select_ AggregationNode()
If(event raised )
   while( the Timer (T_AN) is not expired)
AvgResidualEnergy =
   (1/N) Σ_{k=0}^{N} (NNodeTable[k].residualEnergy)
Assume first node is aggregation node , k = 0,
NNodeTable[k].state = AggrNode;
  for i = 1 to N
      if((NNodeTable[i].residualEnergy >
        AvgResidualEnergy )
        and ( NNodeTable[i].residualEnergy >
         NNodeTable[k].residualEnergy))

          NNodeTable[k].state  = normal
          NNodeTable[i].state  = AggrNode
          k = i
       end if
   end for
     for i= 0 to N
          if((NNodeTable[k].residualEnergy  =
          NNodeTable[i].residualEnergy) and
          (K != i) and
     ( NNodeTable[k].distToSink
                          > NNodeTable[i].distToSink))
             NNodeTable[k].state  = normal
             NNodeTable[i].state  = AggrNode
               k = i
          endif
      end for
if(NNodeTable[k].NodeID  =
                              SELF_SOURCE_ID)
          Broadcast  AggreNode_Msg
     else
          Send the sensed data along with residual
energy to Aggregation Node
  endif
    endwhile
  else
       Broadcast SYNC_Msg for every alternative frame
and  turn into sleep mode
```

Figure 6. Pseduo-code for Node selection for Aggregation

1) *Data Collection at Aggregation Node*

Each node in the network has a neighbour list to keep its neighbour's information such as residual energy, distance to the sink and current state of a node, as shown in the Table-2. During the initialization of the wireless sensor network, every node broadcasts Beacon_Msg using transmission radios r, the message includes node ID, residual energy and shortest distance to sink. On receiving these messages, node updates its neighbour node table. In aggregation node selection stage of data collection phase, every node uses the following equation to compute the average residual energy of neighbour nodes.

$\mathrm{AvgR_E} = \frac{1}{N}\sum_{k=0}^{N}(R_E)_k$ ------ (3)

Where N is total number of event affected sensor nodes, $(R_E)_k$ residual energy of k^{th} node, R_E is residual energy.

Table -2 Node 15's neighbour nodes table

NodeID	Residual Energy (J)	Distance To Sink	State
15	2.46	25	normal
17	2.09	30	normal
9	2.78	20	normal
25	1.06	40	normal
43	2.78	35	normal
31	2.78	45	normal

Event Data collection at aggregation node is similar to TDMA and the data communication between the aggregation node to sink node is similar to T-MAC. In our proposed system, Aggregation Node prepares the sleep wake up schedule based on the priority of event affected nodes. The priority of the nodes is decided based on the residual energy levels of the nodes. The lowest residual energy of the node will have highest priority to send its data and it's getting more time for sleeping. If more than one node is having same residual energy, in such cases there could be chances of getting the same priority for more than one node. Therefore we are considering one more criteria, the distance to aggregation node, to select the priority. The total wakeup time of the nodes decides on the size of the data and SYNC message to transmit, waiting for ACK message from the AggNode as in Equation 4.

$T_{act} = T_{data} + T_{sync} + T_{ACK}$ ----- (4)

$T_{data} = \frac{l}{b}$ ------ (5)

Where T_{data} total time required transmitting the *l* data size in network bandwidth b.
T_{sync} time required for SYNC message.
T_{ACK} is time required to receive the ACK message from AggNode.

Node which is transmitting the data will wakes up on it's scheduled time period and sends the data as shown in the Figure 7. On receiving the ACK message from the AggNode; the node broadcasts the SYNC_msg which is having the residual energy and next wake up time before its going to sleep. In the proposed system overhearing problem have been avoided as all nodes which are located in the event trigged area will be in sleep state except the AggNode and the node which is sending the data. The AggNode will be active for complete data transfer cycle and collects the data. On successful event data collection , it aggregates the data before sending to the sink node.

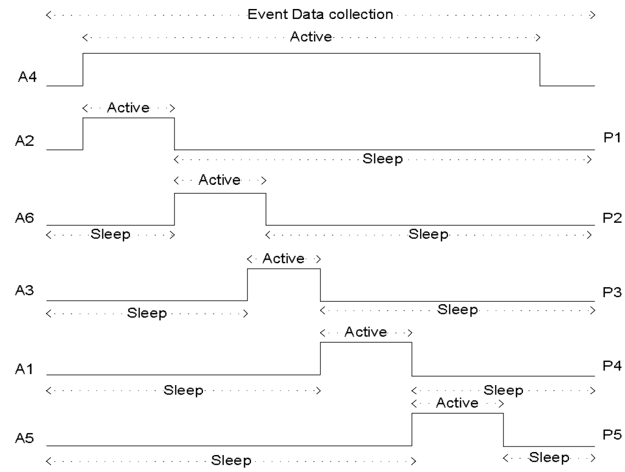

Figure 7 Data Collection at Aggregation node

In case of huge data transfer from multiple sensors, data packets can be converted into small packets and can be sent across using the shared transmission medium. Smaller data packet from multiple source can be placed in any order as long as there is available bandwidth to carry it. Each data packet contains the destination address and sequence number and it will help the receiver node to reconstruct the node data if required and sent to the proper recipient. Our method utilize the full extent of available network bandwidth for data transmission and it helps in reducing the waiting time of the contender nodes.

IV. SIMULATION

We have following assumptions in our simulation setup: 1) Sensor nodes are static and there is only one sink node; 2) Nodes are location aware and know their distance from the sink node.
We used the simple energy model explained in [19] for energy consumption evaluation. The energy consumption for sending *l*-bits data to distance d is E_{Tx} and energy consumption for receiving *l*-bits data is E_{Rx} The energy model used as shown in the following equations (6) and (7)

$E_{Tx}(l\text{-bits}, d) = l\text{-bits}(E_{dpb} + \xi fs * d^2)$ ------- (6)

And energy for receiving the *l*-bits data bit is equal to

$E_{Rx}(l\text{-bits}) = l\text{-bits} * E_{dpb}$ ------- (7)

Where ξfs is constant and ξfs = 100 pJ/bit/m2 and Edpb = 50nJ/bit, E_{dpb} is energy dissipated per bit .

Event affected nodes start the computing to select the aggregation node and processing the data within small time period, therefore data processing inserts no extra latency.

1) Energy Consumption Evaluation

Table 3: Simulation parameter

Parameter	Values
Number of nodes	36
Simulation time	160s
Date Rate	250kbps
Bandwidth	20MHz
Path loss factor	55 dBm
Reference to distance d0 d0 = 1 meter	
Power Consumption during the state change	
Tx to Rx or Rx to Tx	62ms
Rx/Tx to SLEEP	1.4ms
Initial Energy	18720J

We have evaluated the energy efficiency of our proposed data aggregation and MAC protocol. We used the Castalia 3.2 simulator along the simulation parameter as depicted in the Table -3. The average energy consumption is calculated to transmit the event data by the event affected nodes to sink. The power consumption of our proposed algorithms have been compared with T-MAC and S-MAC as shown in the Figure 8. The proposed algorithm consumes less energy compare to T-MAC and S-MAC. There are reasons for this, one is adaptive selection of aggregation node and AggNode computes the active/sleep schedule based on the data size as shown in the Figure 7, it avoids the RTS/CTS control messages and ideal listening.

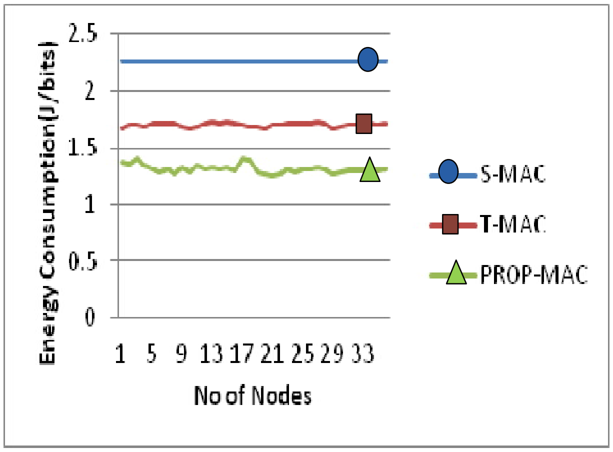

Figure 8 Energy consumption of Nodes

2) Latency Evaluation

We have evaluated the performance of end-to-end latency and compared the proposed protocol performance with T-MAC and S-MAC. The latency in T-MAC , S-MAC and proposed MAC protocol increases as the traffic load increases. We observed the lower latency in our proposed MAC protocol compared to T-MAC and S-MAC, because the data collection happens in aggregation node and it transmits the aggregated data to sink . In case of T-MAC and S-MAC all nodes are participating to send their data to sink.

V. Conclusion

In this paper , we have proposed an energy efficient algorithm to select a data collection node for aggregation and MAC protocol which offers variable data transfer slot depending on the size of available event data to sink node. The selection of aggregation node adaptively initiates when event occurs and only single node will be sending the data to sink after the data aggregation. This avoids the unnecessary contention and reduces the latency. When the node is transmitting the data to Aggregation Node in its predefined time slots, other nodes will be in sleep state, which reduces the overhearing. Simulation results indicate that our protocol's performance achieves much better results than T-MAC and S-MAC protocol.

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