EEDF-MAC: An Energy Efficient MAC Protocol for Wireless Sensor Networks

Maaz M. Mohiuddin, Adithyan I., P Rajalakshmi
Department of Electrical Engineering
Indian Institute of Technology Hyderabad
Hyderabad, India
Email: {ee09b015, ee09b001, raji}@iith.ac.in

***Abstract*—Recent advances in wireless technology have brought us closer to the vision of pervasive wireless sensor networks. In sensor networks, the nodes have limited energy resources and the applications generally demand timely delivery of the packets. Therefore, high energy efficiency and reduced latency are of paramount importance. The medium access control layer plays a crucial role in managing the energy spent on communication and keeping the latency in check. In this paper, a real time wireless media access control protocol based on earliest deadline first scheduling scheme is proposed. Unlike its predecessors, this new protocol is applicable to both event-driven and clock-driven nodes with salient features being high energy efficiency and priority based latency. We establish the improved latency performance over carrier sense multiple access protocol, through simulation of wireless sensor network in network simulator-3. Then, we present a mathematical model to obtain the lower bound on the fraction of energy saved by the use of the proposed protocol as opposed to existing protocols. This improvement in latency performance facilitates an increase in cluster size and energy efficient communication ensures increased lifetime of the sensor network, which makes our protocol a promising choice for the future wireless sensor networks.**

***Index Terms*—Media Access Control, Prioritized Latency Reduction, Energy Efficient Protocol, Earliest Deadline First**

I. Introduction

With the availability of small, low-cost and low-power sensors, radios, and micro-controllers the vision of ubiquitous wireless sensor networks(WSNs) has become a reality [1]. However, it is seen that the deployment of large WSNs is often limited by high latency in data delivery and low battery life-time [3]. These problems stand in the path of the tremendous growth WSNs are forecasted to have in the coming years [2]. In literature, multiple solutions have been proposed to reduce the latency involved in a large network. Also, a few energy efficient communication techniques have been proposed to increase the life-time of WSNs [5], [6]. In [5], the authors try to extend the lifetime through adaptive sleep and [6] presents a survey and formal analysis of a variety of network lifetime maximization problems in different energy consumption models.

One way to attack the above mentioned problems is to employ an intelligent media access control(MAC) layer. A MAC protocol regulates channel access, i.e. it specifies when a node can transmit and when it is expected to receive data. A good channel access mechanism is one which ensures timely delivery of packets, avoids collisions among nodes and saves energy [8]. Thus by designing an intelligent MAC layer, one can expect an increase in the energy efficiency of the network and also a significant reduction in the latency.

MAC protocols can be broadly classified into two classes [9] namely, contention based(CB-MAC) and scheduling based (SB-MAC). In the class of CB-MAC protocols, the channel access policy is based on competition. There is no schedule a-priori. A Few well known examples of this class of protocols are S-MAC[10], B-MAC[11], CC-MAC[12]. Whereas, in SB-MAC the nodes are allotted slots, which are dynamically updated. Nodes transmit only during allocated slots thereby avoiding contention. Several non-contention based MAC protocols [13] based on scheduling schemes and time division have been proposed. Although the class of CB-MAC protocols performs well when the cluster size is small, the performance of such MAC protocols deteriorate rapidly as the cluster size increases [14]. Due to a very large number of nodes competing for access of the medium, several nodes may experience long delays in transmission, leading to poor latency performance. Furthermore, a lot of energy is wasted in sensing the channel [15] leading to extreme energy inefficiency. Hence, CB-MAC protocols are deemed unsuitable for WSNs [16]. When cluster size is large, which is typical of the future WSNs, the class of SB-MAC protocol perform better.

In some sense, the class of SB-MAC protocol is simply a scheduling algorithm. The challenge of designing a scheduling algorithm suitable for communication networks is an active area of research. Due to rapid changes in the topology of WSNs dynamic priority algorithms are best suited for the scheduling the medium access in a WSN. Dynamic priority algorithms are those where the priority of a task can change during its execution. One of the most important and analysed dynamic priority algorithm is earliest deadline first (EDF)[17]. In this paper, EDF is used as base to develop up an energy efficient scheduling algorithm for WSN which offers low latency for nodes with high priority.

In literature, a few EDF based MAC protocols have been proposed. In [18], the author has presented I-EDF, an EDF based MAC protocol for WSN. The simulation results show an improved delay performance over carrier sense multiple access collision avoidance (CSMA/CA) MAC protocol. CSMA/CA being widely used as a MAC protocol in WSNs serves as a

978-1-4673-6217-7/13/$31.00

good benchmark for comparing the performance of new MAC protocols. An extension of the I-EDF is Robust Implicit EDF (RI-EDF) [19], which uses EDF based scheduling scheme and works well in cases of node failures and topology changes in the network. However, these MAC protocols are designed only for clock-driven nodes i.e. nodes in which the transmission of data is governed by a clock and do not perform well in a WSN with event-driven nodes i.e nodes in which a packet is generated depending on external factors. Secondly, in both these protocols the radios on the nodes are always powered on. This consumes a lot of power and is therefore not energy efficient.

In this paper, we present energy efficient earliest deadline first based MAC protocol(EEDF-MAC). As the name suggests this scheduling algorithm increases the energy efficiency of the network and decreases the latency involved. EEDF-MAC is designed for WSN with both event-driven and clock-driven nodes. In EEDF-MAC, energy efficiency is achieved by turning off the radios of nodes which do not transmit or receive data thereby addressing the emerging problem of increased power consumption in a WSN.

The rest of the paper is organised as follows. In Section II, the terminology and various assumptions involved with EEDF-MAC are introduced. In Section III, the working of EEDF-MAC is discussed. In Section IV, the simulation of EEDF-MAC in network simulator-3 (ns-3) [20] is discussed; the results of latency performance are interpreted and analysed. In Section V, we present a mathematical model to obtain a tight lower bound on the fraction of energy saved when using EEDF-MAC as opposed to CSMA/CA. In addition to a mathematical bound, we also discuss the practically achievable energy savings through a numerical illustration. The conclusions and future scope are presented in Section VI.

II. Terminology and Assumptions

Based on the trigger for data transmission, wireless sensor nodes can be broadly classified into two types, namely clock-driven nodes and event-driven nodes. Clock-driven nodes function based on a periodic schedule decided by the node's internal clock. Generation and transmission of data packets is also periodic and is triggered by an internal clock. Such nodes are usually deployed in applications where environmental parameters are to be constantly monitored. For the ith clock-driven node, the period of data generation is d_i.

On the other hand, data transmission from an event-driven node is triggered by an external agent. Such nodes are usually deployed in safety applications. For instance, a wireless sensor node deployed to report a gas leak in a mine will transmit data only when a casualty occurs. Additionally, different event driven data will have different priority. For example, a slight increase in humidity is far less important than a gas leak in a mine. e_i is the priority assigned to the ith event-driven node and takes values 1,2,3 and so on; 1 being the highest priority.

Given the data rate and the size of the data, the time taken to transmit the data over the wireless channel is also known. Say, t_i is the data transmission time for the ith node. In the above formulation, we have assumed that each node transmits only one type of data. In practice, every node can transmit both event-driven and clock-driven data. In such a scenario, our formulation is applicable with the following modifications.

- Every data in the network is given a unique id.
- d_i is the period of data generation of the ith data, which is of clock-driven type.
- e_i is the priority assigned to the ith data, which is of event-driven type.
- t_i is the data transmission time for the ith data.

In EDF scheduling scheme, time slots are allocated to different processes based on the absolute deadline. The time period of each slot is also the time at which a decision regarding the allocation of next slot is taken. This decision interval T_d is calculated according to (1),

$$T_d = gcd(t_i),\ \vee\ i =\ 1\ to\ n \tag{1}$$

where n is the total number of nodes in the network.

A valid schedule is one in which all the data transmissions are successfully scheduled. The minimum time period required for a valid schedule is called hyper-period of the EDF schedule ($T_{h,EDF}$). The time interval for one hyper-period is computed according to (2).

$$T_{h,EDF} = lcm(d_i),\ \vee\ i\ =\ 1\ to\ n \tag{2}$$

where n is the total number of nodes in the network.

The schedule for one such hyper-period is a function of all ordered pairs (t_i,d_i). If all the ordered pairs remain unchanged for the subsequent hyper-periods, then the schedule for the subsequent hyper-periods will also remain same. From Theorem 7 in [17], it is known that a schedule will exist iff U$\leq$1, where U is given by (3).

$$U = \sum_{i=1}^{n} \frac{t_i}{d_i} \tag{3}$$

where n is the total number of nodes in the network.

In practice the t_i's are of the order of millisecond (*ms*) and d_i's are of the order of second (*s*). Then, each $\frac{t_i}{d_i}$ is of the order of 10^{-3}. Therefore, we can safely assume that a valid schedule will exist for atleast 1000 nodes in one cluster which is far more than the practical requirements.

III. The EEDF-MAC Protocol

The EEDF-MAC protocol can be broadly classified into 4 phases as follows:

1) Network Initialization Phase
2) Schedule Broadcast Phase
3) Data Transmission Phase
4) Synchronization Phase

The following subsections elaborate on the details of information exchange in EEDF-MAC for a single-hop network.

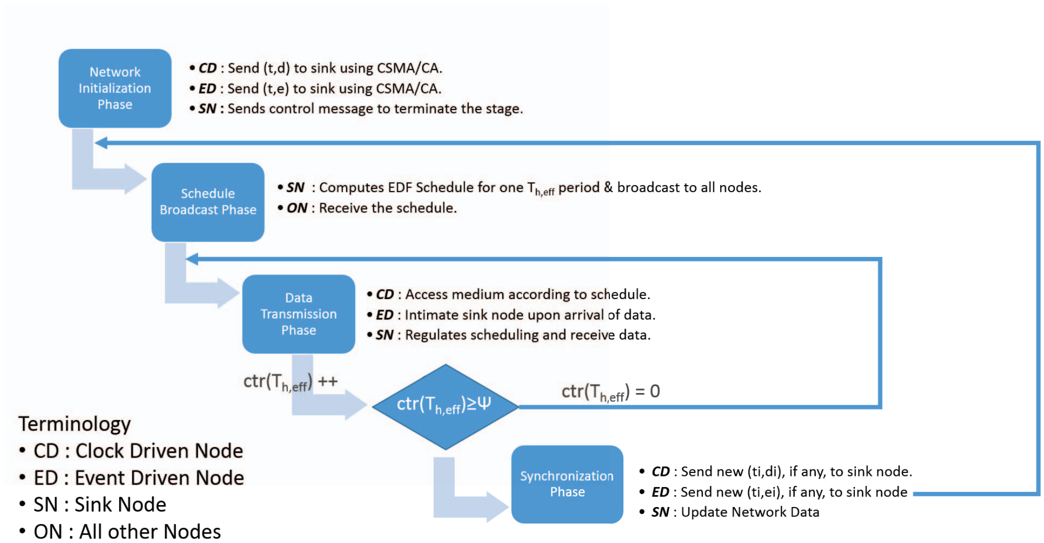

Figure 1. Functions of different types of nodes during each phase of EEDF-MAC

A. Network Initialization Phase

This is the first phase of the MAC protocol and occurs only once when the network is being set up for the first time. The network consists of several clock-driven and event-driven nodes, one sink node. Every clock-driven node transmits (t_i,d_i) to the cluster head using CSMA/CA. Every event-driven node transmits (t_i,e_i) to the sink node using CSMA/CA. The network initialization phase is terminated by a control message from the sink node after reception of the required information from all the nodes in the network.

B. Schedule Broadcast Phase

This is the shortest phase of the MAC protocol. The sink node now knows the total number of event-driven and clock-driven nodes in the network. The sink node computes the schedule for all the clock-driven nodes for one hyper-period based on EDF scheduling scheme. To account for the event-driven nodes in the network, the EDF schedule is padded with time slots T_l. This completes the formation of the access table. T_l is the time during which all the nodes in the network expect a message from the sink regarding the scheduling of event-driven data. The final frame including the schedule for all the clock-driven nodes for one hyper-period and the listening time slots is the effective hyper-period ($T_{h,eff}$). The sink node broadcasts the access table to all the nodes.

C. Data Transmission Phase

This is the longest phase of the MAC protocol. On receiving the access table, the nodes synchronize with the access table. In any period T_d, only the node with the medium access has its radio on and all other nodes have their radio turned off. Hence the power savings. After every $\varphi \times T_d$s, every node turns on its radio for an interval T_l during which the changes in the access table, if any, are received from the sink node. The changes in the access table are due to an arrival of high priority event driven data. φ is decided by the sink node based on the number of event-driven nodes in the network. Intuitively, a network with lot of event-driven nodes will have a low value of φ and a network with less event driven nodes will have a high value of φ. This is because a network with higher number of event-driven nodes will have a higher probability of occurrence of an event. The details of dynamic updating of T_l and φ are presented in the form of algorithm 1.

When an event occurs at a node, the event-driven node communicates e_i to the sink node using CSMA/CA during the next T_l. On reception of the priority information from the node, the sink node looks up for the corresponding data transmission time t_i. In case of multiple events, the sink node computes the schedule for the event driven nodes based on the assigned priorities e_i's. Then, the sink node broadcasts the access table for the event-driven nodes and T_e, where T_e is given by (4).

$$T_e = \sum_{i \epsilon Q} t_i \tag{4}$$

where Q is the set of indices of all the nodes on which an event has occurred.

On receiving a change in the access table, every node defers the access table by a time T_e. The event-driven nodes transmit data according to the received access table and the radio cycles are now synchronized according to the updated access table. This completes the data transmission for one effective hyper-period. This cycle repeats for every effective hyper-period. In this manner, a controlled reduction in latency for high priority (event-driven) data is achieved.

Fig 2 shows an example of an access table. In the second effective hyper-period, clock-driven node with id 1 has the

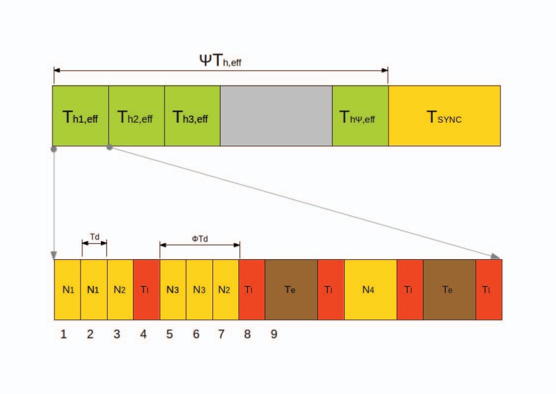

Figure 2. An illustration of an access table

channel access between time instants 1-3, where each time instant corresponds to a time T_d. The channel access for node 2 is pre-empted by node 3. Here, φ is $3 \times T_d$ which is intelligently decided by the sink node. During time instants 1-3, all other nodes except node 1 have their radios turned off. From time instants 4-5, all the radios are powered on to check for any event-driven data in the network. During the listening period from time instant 8, a deferral in access table is received due to an event in the network. Hence, the T_e at time instant 9.

D. Synchronization Phase

The synchronization phase is required to address the changes in the network topology due to node failures or addition of new nodes. This phase occurs after every ψ effective hyper-periods, where ψ is determined based on the frequency of topology changes in the network. A network prone to have rapid topology changes will have a lower value of ψ as opposed to a network with less frequent topology changes.

All the new clock-driven nodes and event-driven nodes with any changes in the timing parameters transmit their respective (t_i,d_i) to the sink node using CSMA/CA. Similar information is transmitted by the event-driven nodes. This information is used to create a new schedule for the next ψ effective hyper-periods. The network data from the previous effective hyper-periods is used to dynamically update T_l and φ according to algorithm 1, so as to achieve higher energy efficiency and latency reduction. The sink node uses metrics like the total number of events occurred since the network set-up (n_{event}), number of hyper periods lapsed since network set-up (n_{hyper}), number of hyper periods in the previous super period ($\triangle n_{hyper}$) and the total number of listening slots (n_l^{sum}), to evaluate T_l and φ for the next super period. T_l is evaluated to approximate to the average number of events during one listening slot. The frequency of listening slots φ is set such that it is close to the frequency of events averaged over the all events until that particular synchronization phase. These dynamic adaptations in listening time and frequency of listening slots make EEDF-MAC robust to changes in network topology.

Fig 1 summarizes the functions of different types of nodes during each of the phases of EEDF-MAC.

Data: T_h , T_{csma}
Result: Evaluation of T_l and φ
Initialization: $n_{event} := 0$, $n_{hyper} := 0$, $\triangle n_{hyper} := 0$, $n_l^{sum} := 0$, n_l;
while *in data transmission phase* **do**
  if *event occurs on an event-driven node* **then**
    $n_{event} \leftarrow n_{event} + 1$;
  end
  if *hyper period is completed* **then**
    $n_{hyper} \leftarrow n_{hyper} + 1$;
    $\triangle n_{hyper} \leftarrow \triangle n_{hyper} + 1$;
  end
end
while *in synchronization phase* **do**
  $n_l \leftarrow \frac{n_{event}}{n_{hyper}}$;
  $\varphi \leftarrow \lfloor \frac{T_h}{n_l} \rfloor$;
  $n_l^{sum} \leftarrow n_l^{sum} + n_l \times \triangle n_{hyper}$;
  $T_l \leftarrow \lfloor \frac{n_{event}}{n_l^{sum}} \rfloor \times T_{csma}$;
  $\triangle n_{hyper} \leftarrow 0$;
end

Algorithm 1: Dynamic updating of T_l and φ

IV. SIMULATION RESULTS

The performance analysis of the proposed EEDF-MAC protocol is studied through simulations in ns-3. We have simulated a single-hop network with an increasing number of clock-driven nodes. The nodes are uniformly distributed around the sink node in a 150 m x 150 m square grid. These dimensions of the square grid are chosen to imitate the node density of a WSN deployed for home monitoring [16]. Fig 3 shows a snapshot from the simulation with 110 nodes in a home area. Every node has 10 packets of same size to be transmitted to the sink node. The size of each packet is 1024 bits and the data rate of the channel is 1Mbps. Hence, the time taken for transmission of a single packet (t_i) would be 1.024 ms.

All the nodes are divided into five categories based on the period of data generation (d_i). For example if there are 21 nodes in our network, 1 node would be the sink node, the remaining 20 nodes would be split into 5 groups of 4 nodes each. Every node in a group will have the same period of data generation. The d_i's chosen in our simulation are 6 s, 8 s, 10 s, 12 s, 14 s. The application was designed in this way to create contention i.e. a specific number of nodes try to transmit data at the same time. This application is primarily aimed at evaluating the latency performance of EEDF-MAC as opposed to that of CSMA/CA with increasing contention in the network. For simplicity, the packet loss due to the wireless channel is assumed to 0 % . Therefore there will

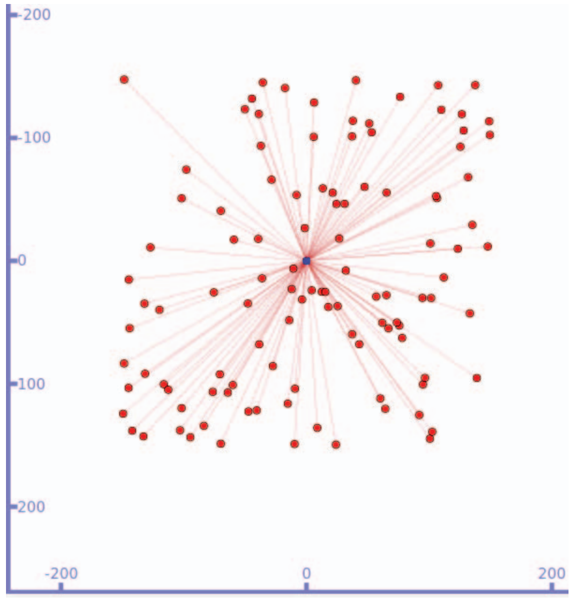

Figure 3. A snapshot from simulation depicting the network topology for 110 nodes in a 150 m x 150 m square grid. The blue dot represents sink node and the red dots represent data nodes

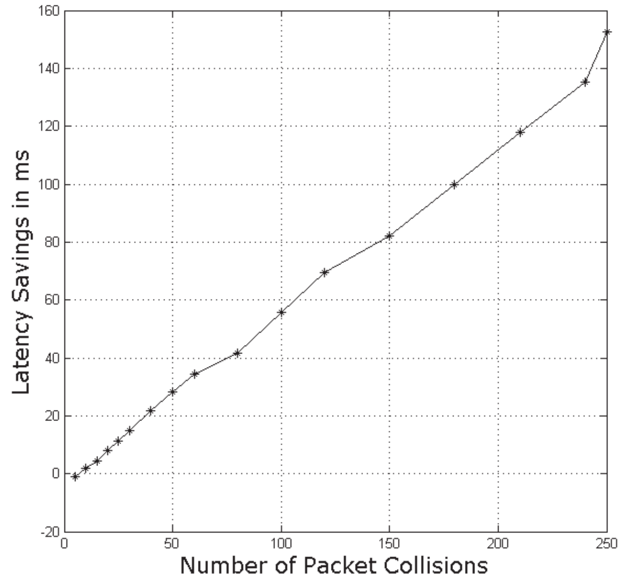

Figure 4. Number of collisions in a single-hop network vs time savings in ms using EEDF-MAC as opposed to CSMA/CA

be no retransmissions due to improper packet reception. This controlled scenario helps in evaluation of latency.

First, simulation is performed for CSMA/CA MAC protocol with increasing number of nodes. The number of nodes considered in the simulation are 6 through 251 in 20 steps. Then we calculate the latency involved. Currently,CSMA/CA is a widely used MAC protocol in various WSN applications. As we intend to study the enhancement in latency performance due to EEDF-MAC over the contemporary contention based protocols, CSMA/CA serves as a good choice for comparison. Then simulation is repeated with EEDF-MAC protocol. We compare the latency performance of EEDF-MAC with CSMA/CA protocol.

Fig 4 shows a plot of number of collisions vs. the average time savings in ms. For lesser contention, the time savings averaged over number of nodes in the network are negative. This means that CSMA/CA MAC protocol has a better average latency performance than EEDF-MAC. However, with an increase in size of the single-hop network and a consequent increase in the number of collisions, the average time savings for EEDF-MAC as opposed to CSMA/CA rise steeply. With the number of collisions close to around 100, the average time saving is close to 150 ms, which is equivalent to the time taken to transmit 150 data packets. This remarkable latency performance makes EEDF-MAC a much better choice for larger networks.

Finally, we will characterise the convergence of EEDF-MAC to existing MAC protocols under the extreme cases of all event-driven and all clock-driven nodes. When all the nodes in the network are event-driven, EEDF-MAC converges to CSMA/CA. However, the latency performance of the protocol will be slightly worse than that of CSMA/CA as it involves communication of request for transmission to the sink node using CSMA/CA followed by reception of schedule through broadcast from the sink node. The latter step being extra, slightly increases the time delay in the network. On the other hand, when all the nodes in the network are clock-driven, EEDF-MAC converges to I-EDF.

V. A Lower Bound on Energy Savings

Consider an n node WSN where each clock-driven node is characterised by the pair (t_i, d_i). Let each node be characterised by a transmitting power P_t and a listening power P_l. The energy spent during transmission and listening radio states in both CSMA/CA and EEDF-MAC is computed and a lower bound on the fraction of listening energy saved is obtained. The two protocols are compared for energy efficiency for one super-period which includes ψ effective hyper-periods and one synchronization phase. The number of data transmission time slots in one hyper-period n_{T_d} is given by (5).

$$n_{T_d} = \frac{lcm(d_i)}{gcd(t_i)} \tag{5}$$

Let ϕ be the ratio of number of transmission periods to listening periods as determined by the sink node. Then, the number of listeing time slots in one effective hyper-period n_{T_l} is obtained by (6)

$$n_{T_l} = \frac{n_{T_d}}{\phi} \tag{6}$$

Hence the total time under consideration T_t is,

$$T_t = \psi T_{h,eff} + T_{sync}$$

where,

$$T_{h,eff} = T_{h,EDF} + n_{T_l} T_l \tag{7}$$

$T_{h,eff}$ is as indicated in Fig 2.

Note: The number of new nodes introduced in the network and the number of changes in (t_i, d_i) is quite small compared to the number of nodes n. Consquently the energy spent exchanging the control inormation regarding the changes in the network topology during T_{sync} is signinficantly small when compared to T_t. Therefore, T_t is given by,

$$T_t \approx \psi T_{h,eff} \tag{8}$$

A. Case 1: CSMA/CA

$$E_{tx}^{CSMA} = P_t T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \tag{9}$$

$$E_l^{CSMA} = P_l \left[nT_t - T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] \tag{10}$$

$$E_{total}^{CSMA} = P_t \left[T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] + P_l \left[nT_t - T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] \tag{11}$$

where E_{tx}^{CSMA} is the energy consumed by n nodes for data transmission, E_l^{CSMA} is the energy consumed by the radios of n nodes during listening state and E_{total}^{CSMA} is the total energy consumed in the WSN when CSMA/CA MAC protocol is used.

B. Case 2: EEDF-MAC

$$E_{tx}^{EEDF} = P_t \left[T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] \tag{12}$$

$$E_l^{EEDF} = nP_l \psi n_{T_l} T_l \tag{13}$$

$$E_{total}^{EEDF} = P_t \left[T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] + nP_l \psi n_{T_l} T_l \tag{14}$$

where E_{tx}^{EEDF} is the energy consumed by n nodes for data transmission, E_l^{EEDF} is the energy consumed by the radios of n nodes during listening state and E_{total}^{EEDF} is the total energy consumed in the WSN when EEDF-MAC protocol is used.

C. Fraction of Listening Energy Saved

$$E_l^{saved} = E_l^{CSMA} - E_l^{EEDF} \tag{15}$$

From (10) and (13),

$$E_l^{saved} = P_l \left[nT_t - T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right] - P_l n \psi \frac{n_{T_d} T_l}{\phi} \tag{16}$$

From (7),

$$E_l^{saved} = P_l \left(\psi T_{h,EDF} + \psi n_{T_l} T_l \phi \right) \left(n - \sum_{i=1}^{n} \frac{t_i}{d_i} \right) \tag{17}$$

Upon further simplification,

$$E_l^{saved} = P_l \psi \left(nT_{h,EEDF} - \frac{T_t}{\psi} \sum_{i=1}^{n} \frac{t_i}{d_i} \right) \tag{18}$$

The fraction of listening power saved by using EEDF-MAC as opposed to CSMA/CA MAC protocol is given by (19)

$$E_l^{frac} = \frac{\psi \left(nT_{h,EEDF} - \frac{T_t}{\psi} \sum_{i=1}^{n} \frac{t_i}{d_i} \right)}{\left[nT_t - T_t \sum_{i=1}^{n} \frac{t_i}{d_i} \right]} \tag{19}$$

To obtain a lower bound for E_l^{frac}, we use the relations

$$\frac{t_i}{d_i} \le max(\frac{t_i}{d_i}) \tag{20}$$

$$\frac{t_i}{d_i} \ge min(\frac{t_i}{d_i}) \tag{21}$$

Applying (20) and (21) in (19) the inequality obtained is

$$E_l^{frac} \ge \frac{\psi T_{h,EDF} - T_t max(\frac{t_i}{d_i})}{T_t(1 - min(\frac{t_i}{d_i}))} \tag{22}$$

Generally $\frac{t_i}{d_i}$ is of the order of 10^{-3}, hence

$$1 - max(\frac{t_i}{d_i}) \approx 1 \tag{23}$$

$$1 - min(\frac{t_i}{d_i}) \approx 1 \tag{24}$$

Applying (23) and (24) in (22) and simplifying,

$$E_l^{frac} \ge 1 - \frac{n_{T_d} T_l}{\phi T_{h,eff}} \tag{25}$$

Clearly, E_l^{frac} is a function of the ratio of listening time to data transmission time in one effective hyper-period. For a purely clock-driven network, ϕ is infinity (∞) i.e. there is no listening after data transmission in EEDF-MAC. In such a scenario, E_l^{frac} equals one, which means that all the energy spent on channel sensing in CSMA/CA is saved when EEDF-MAC is used. As the number of event-driven nodes in a WSN increase, ϕ decreases and so does E_l^{frac}. Fig 5 shows the variation of E_l^{frac} with respect to ϕ for a single hop 251

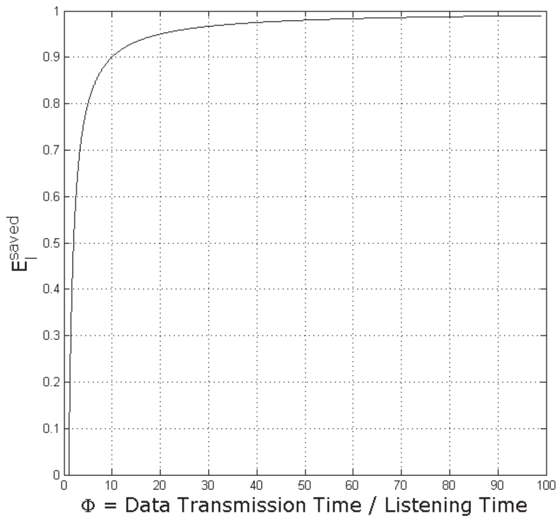

Figure 5. Fraction of listening energy saved vs ratio of listening time to data transmission time for the 251 node network described in section IV

node network as described in Section IV. It is observed that, for ϕ = 6, E_l^{frac} is close to 0.85. Therefore, if the nodes listen to channel after every 6 ms instead of continuously sensing the channel, 85% of the energy spent in listening is saved.

VI. Conclusion

In this paper, we presented EEDF-MAC, a schedule based MAC protocol which achieves energy efficiency by turning off the radio on the nodes which are neither in transmission nor in reception state. It is shown that this protocol performs well in a network with both clock-driven and event-driven nodes as opposed to the previous EDF based MAC protocols which were designed only for clock-driven nodes. The simulation results have shown remarkable latency performance as against CSMA/CA, the widely used MAC protocol in WSN. Such a latency performance allows an increase in the cluster size, which for long has been a limitation in WSN. It is also shown that the lower bound on the fraction of listening energy saved is a function of the ratio of listening time to data transmission time and practically, 80-95% of the energy spent on listening can be saved by using the proposed EEDF-MAC protocol. This energy efficiency coupled with improved latency performance make EEDF-MAC an excellent choice for implementation in WSN.

In the future, we intend to evaluate the performance of EEDF-MAC by physical implementation in a network. We also intend to develop a rigorous mathematical model for EEDF-MAC to lay theoretical bounds on the performance of the protocol. Finally, in view of the upcoming mobile nodes in WSN, the current protocol requires modifications to incorporate support for mobility.

References

[1] Hempstead, Mark, et al. "An ultra low power system architecture for sensor network applications." Computer Architecture, 2005. ISCA'05. Proceedings. 32nd International Symposium on. IEEE, 2005.

[2] Aboelaze, Mokhtar, and Fadi Aloul. "Current and future trends in sensor networks: a survey." Wireless and Optical Communications Networks, 2005. WOCN 2005. Second IFIP International Conference on. IEEE, 2005.

[3] Demirkol, Ilker, Cem Ersoy, and Fatih Alagoz. "MAC protocols for wireless sensor networks: a survey." Communications Magazine, IEEE 44.4 (2006): 115-121.

[4] Anastasi, Giuseppe, et al. "Energy conservation in wireless sensor networks: A survey." Ad Hoc Networks 7.3 (2009): 537-568.

[5] Anastasi, Giuseppe, Marco Conti, and Mario Di Francesco. "Extending the lifetime of wireless sensor networks through adaptive sleep." Industrial Informatics, IEEE Transactions on 5.3 (2009): 351-365.

[6] Dong, Qunfeng. "Maximizing system lifetime in wireless sensor networks." Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on. IEEE, 2005.

[7] Jain, Neha, and Dharma P. Agrawal. "Current trends in wireless sensor network design." International Journal of Distributed Sensor Networks 1.1 (2005): 101-122.

[8] Ephremides, Anthony. "Energy concerns in wireless networks." Wireless Communications, IEEE 9.4 (2002): 48-59.

[9] Kabara, Joseph, and Maria Calle. "MAC Protocols Used by Wireless Sensor Networks and a General Method of Performance Evaluation." International Journal of Distributed Sensor Networks 2012 (2012).

[10] Ye, Wei, John Heidemann, and Deborah Estrin. "An energy-efficient MAC protocol for wireless sensor networks." INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 3. IEEE, 2002.

[11] Polastre, Joseph, Jason Hill, and David Culler. "Versatile low power media access for wireless sensor networks." Proceedings of the 2nd international conference on Embedded networked sensor systems. ACM, 2004.

[12] Vuran, Mehmet C., and Ian F. Akyildiz. "Spatial correlation-based collaborative medium access control in wireless sensor networks." Networking, IEEE/ACM Transactions on 14.2 (2006): 316-329.

[13] Busch, Costas, et al. "Contention-free MAC protocols for wireless sensor networks." Distributed Computing (2004): 245-259.

[14] Younis, Ossama, Marwan Krunz, and Srinivasan Ramasubramanian. "Node clustering in wireless sensor networks: Recent developments and deployment challenges." Network, IEEE 20.3 (2006): 20-25.

[15] Yadav, Rajesh, Shirshu Varma, and N. Malaviya. "A survey of MAC protocols for wireless sensor networks." UbiCC journal 4.3 (2009): 827-833.

[16] Akyildiz, Ian F., et al. "A survey on sensor networks." Communications Magazine, IEEE 40.8 (2002): 102-114.

[17] Liu, Chung Laung, and James W. Layland. "Scheduling algorithms for multiprogramming in a hard-real-time environment." Journal of the ACM (JACM) 20.1 (1973): 46-61.

[18] Caccamo, Marco, et al. "An implicit prioritized access protocol for wireless sensor networks." Real-Time Systems Symposium, 2002. RTSS 2002. 23rd IEEE. IEEE, 2002.

[19] Crenshaw, Tanya L., et al. "A robust implicit access protocol for real-time wireless collaboration." Real-Time Systems, 2005.(ECRTS 2005). Proceedings. 17th Euromicro Conference on. IEEE, 2005.

[20] ns-3-The Network Simulator, http://www.nsnam.org, 2011.