ENERGY EFFICIENT SCHEDULING IN CROSS LAYER OPTIMIZED CLUSTERED WIRELESS SENSOR NETWORKS

Jayanthi K. Murthy[1], Suthikshn Kumar[2] and Srinivas A.[3]

[1]Department of E and C, BMS College of Engineering, Bangalore, India, *jayanthi.ece@bmsce.ac.in*

[2]Department of Electronics, Defence Institute (DIAT), Pune, India, *suthikshnkumar@diat.ac.in*

[3]Department of E and C, PES Institute of Technology, Bangalore, India, *a.srinivas@pes.edu*

———— ABSTRACT ————

In this paper, we present an energy efficient scheduling algorithm for clustered wireless sensor networks. The main objective is to provide optimized Time Division Multiple Access (TDMA) schedules that can acquire high power efficiency, reduced interference, reduced conflict and reduced end-to-end delay over a wide network. To obtain this objective, a joint optimal design of network, medium access control (MAC) and physical layers is considered to reduce the overall energy consumption. The slot reuse concept is applied to derive the TDMA schedule to minimize the frame length. The numerical results reveal that the presented solution reduces per bit energy consumed and end-to-end delay significantly.

Keywords: Wireless Sensor Networks, cross-layer optimization, TDMA schedule, slot reuse, power efficiency.

1. INTRODUCTION

Wireless sensor networks usually consist of thousands of sensors which are deployed densely and randomly. Each sensor has a low weight and low cost with the capability of sensing, processing and transmission. Sensor nodes are limited by the battery power that leads to limited lifetime of a sensor network. Maximizing the network lifetime is the common objective of sensor network research.

Designing of MAC layer protocol for WSN's is a challenging task due to limited battery power and limited bandwidth. Time Division Multiple Access (TDMA) is said to be more effective than contention based protocols such as Carrier Sense Multiple Access (CSMA) especially when the traffic load is very high. [1] Two important issues in WSN are:

1. Saving the battery power to increase the lifetime of the network.

2. Fast and efficient query response, to detect change in the environment immediately.

Based on the above characteristics, the TDMA protocol must be energy efficient by reducing the potential energy wastes and send the sensed data to the sink without further delay. TDMA protocols reduce data retransmissions because collision does not occur in TDMA protocol. One of the major challenges in adopting TDMA MAC is finding the efficient time-schedule.

In this paper, our main objective is to derive the TDMA schedules with optimized energy consumption in clustered WSN's. TDMA scheduling can be defined as the process of allocating time slots to the nodes, or links between each pair of neighbouring nodes, to obtain collision free channel access.

To achieve our objective, we derive the TDMA schedule by a two-step approach. We first find the optimum per bit energy required for transmission on each link by a joint design of physical, medium access control and network layers. Then the optimal flow distribution is determined based on the calculated optimal power consumption. Then the slot reuse concept is applied to obtain the TDMA schedule. The slot reuse concept reduces the end-to-end delay without an increase in the energy consumption.

The organization of paper is as follows: Section 2 provides a literature survey of the related work. Section 3 presents the joint layer optimization. Section 4 describes the scheduling algorithm used to obtain energy efficiency. Section 5 presents the numerical results. The paper is concluded in Section 6.

2. LITERATURE SURVEY

Previous works on TDMA scheduling mainly concentrate on obtaining the smallest length schedules [2] [3], or distributed implementation [4] [5] [6]. The authors in [2] obtain non-conflicted TDMA schedules first, an algorithm then runs through all the nodes and slots, to produce maximal broadcasting sets to reduce the schedule length. The authors of [3] consider the number of packets being sent at every node and provide an algorithm to obtain the shortest schedules by eliminating the nodes without packets to send at each loop. Both these algorithms require global topology information, which

may be difficult for large size networks. To overcome this difficulty, many distributed schemes such as DRAND [4], PACT [5], TRAMA [6], and the Depth First Search (DFS) scheme used in [2] have been proposed. These approaches provide schedules by exchanging messages between local nodes by obtaining local topology and interference information at each node.

Recently, cross-layer design has been combined with TDMA scheduling to increase the network lifetime. The authors in [7] uses joint link scheduling and power control with the objective of energy efficiency subject to QoS guarantees in terms of bandwidth and bit-error rate. The authors in [8] use joint optimization of physical, MAC and network layers to obtain the interference-free TDMA schedules. In [9], optimization problem is solved by using interior point method in order to increase the network lifetime. A single frame without slot reuse for the whole network reduces the interference but increases the end-to-end delay. Joint layer optimization and slot reuse concept has been combined by the authors in [7] to derive energy efficient schedules.

The scheme to improve the energy efficiency is based on the cross-layer optimization. We calculate the conflict-free TDMA schedule utilizing the slot reuse concept similar to the approach used in [1] and [8]. This approach exhibits four differences compared to the previous works: First, our approach improves the energy efficiency and minimizes the delay. Second, the slot reuse concept is applied by considering the distance between the nodes so that the interference is reduced. Third, the proposed algorithm is flexible, and can be applied to both clustered and non-clustered WSN's. The distance between the nodes where the slots are reused is also taken into consideration before reusing the slot.

3. JOINT-LAYER OPTIMIZATION

In this section, the physical, MAC and network layer models that serve as input to the joint layer optimization model and wireless sensor network architecture is presented.

Energy Performance in Wireless Sensor Networks can be improved by designing energy aware hardware and software. Energy aware software approach includes development of energy efficient communication protocols and employing the benefits that can be obtained through cross layer interaction among the layers. In resource constrained WSN's, the lifetime of the network can be increased by optimization which can be achieved by exchanging the information across all the layers.

The network architecture is as follows:

The nodes in the network are divided into clusters, each consisting of a cluster head (CH) and a gateway (GW). The cluster members of the cluster communicate with the cluster head via one hop. The transmission range of the cluster heads and gateways is not restricted to one hop. The clustering scheme presented in [10] can be used

to form clusters. The analysis is simplified by using virtual link to represent the traffic from a cluster member to the corresponding cluster. Thus the TDMA schedule is derived considering only the backbone network consisting of cluster heads and gateways.

A graph G (V, L) is used to denote the backbone network consisting of CH's and GW's including sink, V represents the set of nodes and L represents the set of links. The total number of nodes in the network is $n = |V|$. The sink is considered as node 1. The links are considered to be unidirectional so that the link (i, j) is different from link (j, i). We assume that the sensor nodes are stationary in the network.

Physical layer links various parameters such as power, Signal to Noise ratio (SNR) and bit error rate together by considering the propagation model, modulation and demodulation, encoding and decoding techniques. The path loss model [11] used is:

$$Pl\ (d) = Pl\ (d_0)\ 10\ \gamma \log 10(d/d_0) \tag{1}$$

Where d is the distance between the transmitter and receiver, d_0 is the reference distance and γ is the path loss component.

The bit error rate expressed as a function of SNR for the non-coherent FSK MODEM scheme used in Mica2 motes is given by

$$P_e = \tfrac{1}{2}\ (e^{\text{SNR}/2*B_N/R}) \tag{2}$$

Where R is the data rate in bits per second (*bps*), and B_N is the noise bandwidth.

The SNR at the receiver located at a distance d from the transmitter is given by:

$$SNR(d)_{dB} = P_{tr\ dBm} - Pl(d)_{dB} - P_{n\ dBm} \tag{3}$$

Where the parameters on the right hand side are the transmission power, the average path loss at the distance d, and the noise floor.

Considering the length of the packet as L bytes and the encoding data rate is ρ, then the packet loss rate p on each link is defined as the probability that at least one transmitted bit in a packet is corrupted is given by [1],

$$p = 1 - (1 - P_e^{\ 8\rho L}) \tag{4}$$

The energy consumed for sensing is assumed to be small and is neglected. The average transmission energy consumption by node a, to transmit a data bit to node b with transmit power $P_{tx,ab} = P_{cir,tx} + P_{tx}\ (d_{ab})$, is given by [1],

$$\text{and,} \qquad E(P_{tx,ab}) = 1/R(P_{clr,\ tx} + P_{tx}\ (d_{ab})) \tag{5}$$

Where $P_{cir,\ tx}$; power consumed by the transmitter circuits (excluding the power consumed by the power amplifier circuit), which is a constant. $P_{tx}(d_{ab})$: Power consumed by the power amplifier circuit to transmit a distance d_{ab}, $P_{tx,ab}$ is variable depending on the

transmission distance d_{xy} and the packet loss rate. The per bit average receiving energy consumption at receive power P_{rx} is fixed and is calculated by:

$E(P_{rx}) = P_{rx} / R$, where P_{rx} is the power consumed by the receiver circuits.

The MAC layer protocol employed in the data relay phase is TDMA. A TDMA frame consists of a number of slots, each with fixed length Δt. Increasing the transmission power can reduce the bit error rate. This shows that an optimal transmission power exists for each and every link.

Multihop, multipath routing is performed at the network layer. The sink provides the information of the next hop and the proportion of data traffic to the next hop to every CH or GW after deriving the optimal schedules at the end of the initialization phase of every round.

Combination of all the three layers gives the joint-layer design. A cross-layer optimization can be formulated as in [1].

4. THE TDMA SLOT REUSE ALGORITHM

From the optimization model, the optimal values of transmission power and the flow distribution on every link for the energy efficient data relay can be obtained as in [1]. Here, we adopt a simple method to calculate the TDMA schedule that has the shortest length. The algorithm starts from any of the backbone nodes (CH or GW). Slots are first assigned to the virtual link if the node is a CH and then to all the outgoing links of the node. The algorithm checks all the links that are previously assigned before assigning the slots to any succeeding nodes to ensure that there is no conflict. The four conditions that must be satisfied before assigning slots to any link of node i, $i \in [2, N]$ are as follows:

Condition 1: The current node should neither be the sender or receiver of a previously scheduled link using slot s, and the receiver of this link must not be any link scheduled with slot s.

Condition 2: There should be no interference to the slot scheduled by node i with the links already scheduled to use slot s.

Condition 3: The sender of the scheduled link using slot s should cause negligible interference to the current receiver if it is using slot s on one of node $i's$ links.

Condition 4: Apart from the above three conditions, we also ensure that the distance between the node being assigned slot s and the node to which slot s was previously assigned is greater than 40m so that the interference is less than 10 percent of the noise floor. If the interference is less than 10 percent of the noise floor, we assume that the interference at a node is negligible.

The TDMA slot reuse algorithm can be described as follows:

1. For each node i ($i \neq$ sink) of V.
2. For each required slot m in M_i, Start from slot $s = 1$.
3. Check for the satisfaction of the first three conditions.
4. If all the three conditions are satisfied, check the distance between the current node and all the nodes to which the slot was previously assigned.
5. If distance between nodes > 40m, $s = 1$ can be reused and assigned to current node.
6. Else $s = s + 1$ and repeat steps 3 to 5.
7. Store the id of the last slot s assigned to node i, Lastslotidi = s.
8. Calculate the frame length $M = $ max (Lastslotid$_i$), for all $i \in [2, N]$.
9. Check $M \Delta t \leq 1$. If $M \Delta t > 1$, decrease the value of Δt and repeat the algorithm for the new value of Δt until $M \Delta t \leq 1$.

5. SIMULATION RESULTS

Simulation was done in MATLAB. The parameter values are selected assuming Mica2 motes. We set $R = $ 15kbps, 19.2 kbps and 25kbps. Also $B_N = $ 30 kHz, $\rho = 2$ (Manchester encoding), $F = $ 50 bytes, $P_{cir,tx} = $ 15mW, $P_{rx} = $ 22.2mW, $d0 = 1m$, Pl ($d0$) = 55dB, $\gamma = 4$, and $P_n = $ –105dBm [14]. Lower bound and upper bound of P_{tx} is taken as 10mW and 2001mW respectively and traffic aggregation factor is of cluster head is assumed as $C_i = 1$.

Figure 1 shows the variation of Signal-to-Noise Ratio with distance. It can be observed that as the distance increases, the interference decreases. This variation of interference with distance is taken into consideration in order to reuse the slots. Interference has been considered to be negligible when 10 per cent of SNR is less than 10 per cent of noise floor.
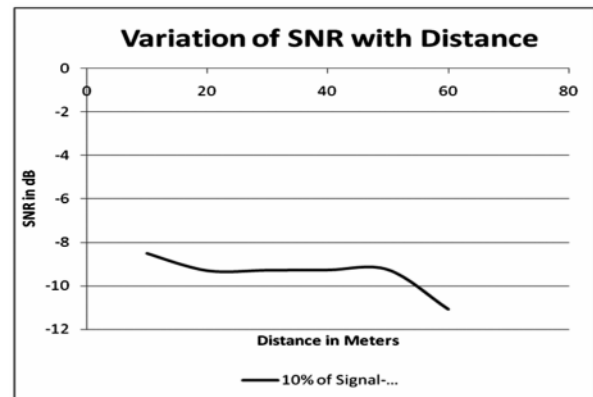

Figure 1: Variation of SNR with Distance

We have also observed the variation in the packet loss rate by varying the maximum data rate. It is observed that the packet loss rate increases as the data

rate increases. So if the packet loss rate increases, the number of required retransmissions also increases.

It has also been observed the variation in the energy consumed when a bit is transmitted from one point to other by varying the maximum data rate. Figure 2 shows the variation of packet loss rate with the variation of maximum data rate. The data rates selected are as follows: $R = 15$ kbps, $R = 19.2$ kbps, $R = 25$ kbps.

We have also observed the energy consumed in the transmission of a bit from one node to other by varying the data rates. It is observed that the energy consumed for the transmission of a bit from one node to other decreases as the data rate increases. Therefore a trade-off should be made when choosing the maximum data rate as seen in Figure 3.
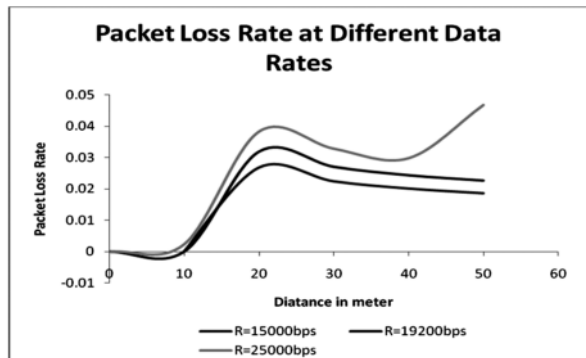

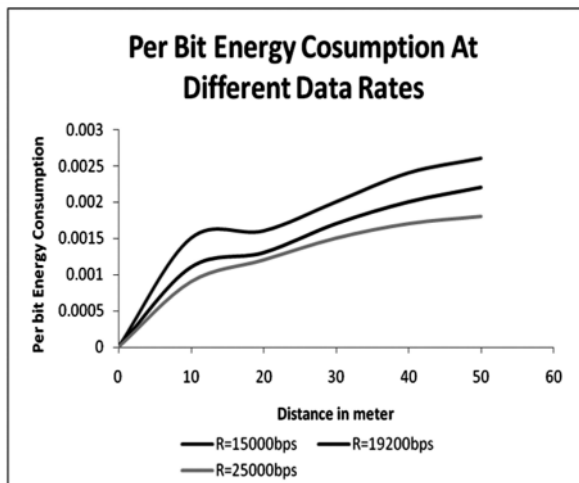Figure 2: Packet Loss Rate at Different Data Rates

Figure 3: Per Bit Energy Consumption at Different Data Rates

From figure 2 and 3 we decide on the optimum values for bit rate as 25kbps, since both energy consumption and packet loss rate is lowest for a distance of 40 meters. To calculate the TDMA schedule, we have considered a backbone network consisting of cluster heads and gateways. By varying the distance between the cluster heads, it is observed that more number of slots get reused. This becomes an advantage for a large size network.

Figure 4 shows a backbone network of 49 nodes, with Cluster heads indicated by square and gateways by triangle.
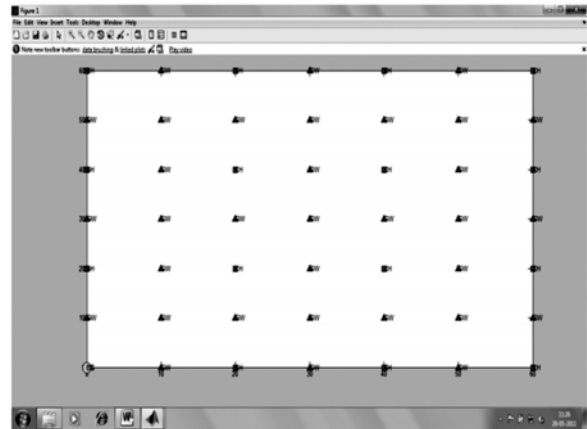

Figure 4: Backbone Network of Nodes, CH is the Cluser Head and GW is the Gateway

Figure 5 shows the Optimal Path Routing and Fig. 6 shows the Shortest Path Routing. The TDMA schedule has been determined for both the relay schemes by varying the distance between the cluster heads. It is observed that as the distance between the cluster heads is increased i.e., as the network size increases, more number of slots can be reused. Thus the TDMA frame length can be minimized. Thus the percentage of delay reduced as the network size is increased.
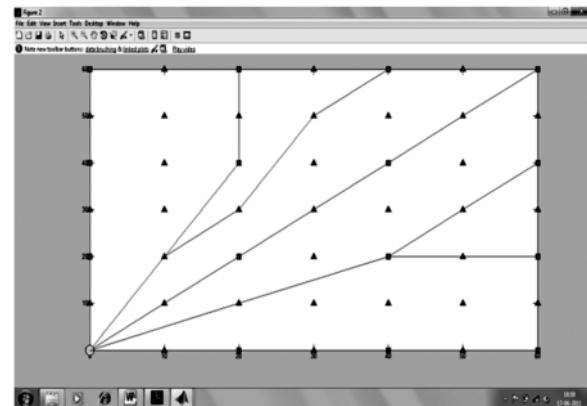

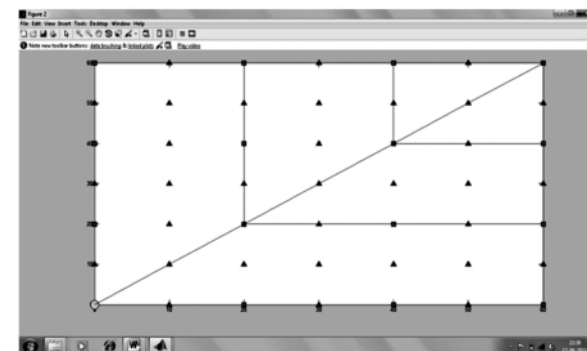Figure 5: Optimal Path Routing

Figure 6: Shortest Path Routing

Table 1 gives the comparison of TDMA frame length and the percentage of delay reduction for Shortest Path Routing with varied distance between the cluster heads.

Table 1
Comparison of TDMA Frame Length and Percentage Delay Reduction with Varied Distance between the Cluster Heads

Relay Scheme	Distance Between The Cluster Heads	No. of Slots Reused	% of Delay Reduced (No. of slots reused/Total no. of slots)
Optimal Path	20m	24	21.05
Shortest Path	20m	22	19.29
Shortest Path	30m	40	35.08
Optimal Path	30m	48	42.10

Table 2 gives the comparison of Percentage of delay reduction using shortest path routing by varying the number of nodes in the backbone network.

Table 2
Comparison of Percentage of Delay Reduction by using Shortest Path Routing by Varying the number of Nodes in the Backbone Network

Number of Backbone Nodes	Distance Between Cluster Heads	No. of Slots Reused	% of Delay Reduced (No. of slots reused/Total no. of slots)
36	10m	0	0
49	10m	24	21.05

6. CONCLUSION

A cross-layer optimization which reduces the per bit energy consumption has been used to schedule a TDMA frame of minimum length. Numerical studies have been done for uniform backbone network topology and the results reveal the effectiveness of scheduling algorithm in the reduction of the TDMA frame length and percentage of delay reduction. In this paper, by considering the distance between the nodes where the slots are reused a low power consumption scheduling algorithm is designed and results indicate that the delay is reduced considerably.

REFERENCES

[1] Liqi Shi, and Abraham O. Fapojuwo, "TDMA Scheduling with Optimized Energy Efficiency and Minimum Delay in Clustered Wireless Sensor Networks", *IEEE Transaction on Mobile Computing*, **9(7)**, pp. 927-939, July 2009.

[2] R. Ramaswami and K.K. Parhi, "Distributed Scheduling of Broadcasts in a Radio Network", *Proc. IEEE INFOCOM*, pp. 497-504, Apr. 1989.

[3] S.C. Ergen and P. Varaiya, "TDMA Scheduling Algorithms for Wireless Sensor Networks", *UC Berkeley Report*, July 2005.

[4] I. Rhee, A. Warrier, M. Aia, J. Min, and M.L. Sichitiu, "Z-MAC: A Hybrid MAC for Wireless Sensor Networks", *IEEE/ACM Transactions on Networking*, **16**, pp. 511-524, 2008.

[5] G. Pei and C. Chien, "Low Power TDMA in Large Wireless Sensor Networks", *Military Communications Conference (MILCOM'01), IEEE*, **1**, pp. 347-351, October 2001.

[6] V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks", *The First ACM Conference on Embedded Networked Sensor Systems (Sensys'03)*, Nov. 2003, pp. 181-192.

[7] U.C. Kozat, I. Koutsopoulos, and L. Tassiulas, "A Framework for Cross-Layer Design of Energy-Efficient Communication with Qos Provisioning in Multihop Wireless Networks", *Proc. IEEE INFOCOM*, **2**, pp. 702-711, Mar. 2003.

[8] R. Madan, S. Cui, S. Lall, and A.J. Goldsmith, "Cross-Layer Design for Lifetime Maximization in Interference-Limited Sensor Networks". *IEEE Trans. Wireless Communication*, **5(11)**, pp. 3142-3152, Nov. 2006.

[9] S. Boyd and L. Vandenberge, Convex Optimization, Cambridge Univ. Press, 2003.

[10] Md. Mamun-or-Rashid, Muhammad Mahbub Alam and Choong Seon Hong, "Energy Conserving Passive Clustering for Efficient Routing in Wireless Sensor Networks", *Proc. IEEE, 9th International Conference on Advanced Communication Technology*, **2**, pp. 982-986, Feb. 2007.

[11] T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd edition, Prentice Hall, 2001.