An Adaptive Energy Efficient Low Latency Sleep Schedule for Target Tracking Sensor Networks

N.A Vasanthi† **and S. Annadurai**††

†Sri Krishna College of Engineering and Technology, Coimbatore, India
††Government College of Technology, Coimbatore, India

Summary
Energy management in sensor networks is a critical issue to prolong the network lifetime. However, the end-to-end latency increases due to energy saving algorithms. We propose a new protocol, ELS (**E**nergy efficient low **L**atency Sleep **S**chedule for Target Tracking Sensor networks), that provides a dynamic sleep schedule for the radios to increase the network lifetime as well as transmit the target's information to the sink with low end-to-end latency. In the surveillance state, the radios of interior nodes are put into sleep using a static schedule. If a target arrives, radio schedule of the nodes nearby the target is dynamically changed to wake up the neighbors and start sensing before the target reaches their location. The intermediate nodes in the target to sink path is activated in order to transmit the information to the sink with low latency. We show theoretically how the energy consumption of the interior and border nodes is balanced using our schedule. Our approach is to (1) increase the network lifetime (2) transmit the target location to the sink with low latency. Simulation results show that ELS provides low latency when compared to S-MAC and increases the network lifetime by 25% more than S-MAC at low load.

Key words:
Target tracking sensor networks, Sleep planning, MAC protocols, Energy consumption, End-to-end latency

1. Introduction

Wireless sensor networks can be used for a number of strategic applications such as coordinated target detection, surveillance, and localization [1], [2], [3]. In target tracking applications, interesting events like movement of an intruder, movement of wild life in forest or reservoirs, or movement of enemy tanks in battle field can be monitored. The goal is to trace the roaming paths of moving objects in the area in which sensors are deployed. The monitoring sensor network should remain at certain level of vigilance, as well as work in an unattended manner as long as possible. The interesting events happen infrequently with long intervals of inactivity. The sensor nodes can stay in sleeping mode during the long intervals of inactivity and be awake in the tracking state. The network operates in two states. In the surveillance state, when there are no events of interest in the field, the sensors should be ready to detect any possible occurrences. In the tracking state, the network should react in response to any moving target and the sensors collaborate in measuring the target's path and speed. An algorithm to alert nodes along the projected path of the target is discussed in [4]. In [5], an energy aware target localization procedure for cluster based networks is proposed. For a target tracking sensor network, though intensive coverage is needed at the time and location of the target event, minimum coverage is enough during the surveillance state.

A given area can be monitored perfectly with a set of sensor nodes to detect targets. Since the sensor nodes have limited power, the quality of monitoring becomes inversely proportional to the lifetime of the network. Power saving operations at each node plays a critical role in extending the network lifetime. The more time the nodes are active, the more power they drain out and hence new nodes should be redeployed in order to monitor the network area. This implies increase of cost for maintenance of the network. On the other hand, the less time the nodes are active, the more power they conserve and hence longer will be the time for redeployment. Hence, energy conservation should be improved by using suitable network protocols. However existing medium access protocols are not specifically designed to track targets with minimum energy consumption.

In our paper, we propose a novel sleep schedule that saves energy by balancing the lifetime of all the nodes to increase the network lifetime. Our sleep schedule conserves energy by allowing more nodes to sleep in the surveillance state and tracks the target with low latency by dynamically changing the schedule.

The rest of the paper is organized as follows. In Section 2, the related work about various types of MAC protocols is presented. The proposed energy efficient low latency schedule for target tracking is presented in Section 3. Theoretical analysis is given in Section 4. The simulation results for performance evaluation are presented in Section 5. Finally, the conclusion is given in Section 6.

2. Related Work

In target tracking sensor networks, nodes are in idle state for most time, when no event happens. It would be a significant waste of energy if all nodes always keep their radios on, since the radio is a major energy consumer. An ideal power conservation policy would switch radios off when a node is not required to act either as a data source or relay in multi-hop routing.

Topology control protocols such as ASCENT [6], SPAN [7], and STEM [8] have been proposed to reduce energy consumption in sensor networks. STEM is a two-radio architecture that achieves energy savings by letting the data radio sleep until communication is desired while the wakeup radio periodically listens using a low duty cycle. However, two-radio architecture is expensive to implement on sensor nodes.

Various contention-based and TDMA-based MAC protocols have been discussed in [9]. TRAMA [10] is a scheduling protocol that allows nodes to switch to the low power idle state whenever they are not transmitting and receiving. It determines which node can transmit at a particular slot based on the traffic information at each node. In [11], event scheduling is used which allows each node to power down its radio during the portion of the schedule that do not match its particular event subscription. However, TDMA-based protocols are not suited for event-based operation, as they cannot increase the resource utilization due to their reservation schemes.

IEEE 802.11 distributed coordination function (DCF) [12] is a CSMA type protocol in which energy consumption is very high due to idle listening of nodes. S-MAC [13] is a contention based protocol with integrated low-duty-cycle operation that supports multi-hop operation. The basic scheme of S-MAC is to put all nodes into periodic listen and sleep. Nodes exchange and coordinate their sleep schedules rather than randomly sleep on their own. However, periodic sleeping increases latency and reduces throughput, since a sender must wait for the receiver to wake up before it can send data. It introduces a mechanism called message passing which modifies the network allocation vector for virtual channel reservation in IEEE 802.11 type of MAC protocols. The major problem with message passing is that it is application-specific and suffers from poor packet-level fairness. T-MAC [14] extends S-MAC by adjusting the length of time sensors are awake between sleep intervals based on communication of neighbors. It reduces idle listening by transmitting all messages in bursts of variable length and sleeping between bursts. Latency in T-MAC increases because data arrived during sleep is queued until the next active cycle. D-MAC [15] follows a periodic active /sleep schedule with an offset that depends upon its depth on the data gathering tree but does not use collision avoidance methods. However, the above mentioned protocols are not meant for target tracking applications and do not focus on balancing the lifetime of all the sensor nodes which are deployed at different parts of the network. Whereas our protocol uses an adaptive sleep schedule to increase the power savings without missing any target detection.

Power conservation in target tracking presented in [16] proposes soft deployment of sensor nodes based on the quality of surveillance. But it does not provide any means for balancing the lifetime of all the nodes to improve the network lifetime. Whereas we focus on improving the network lifetime as well as reduce the latency by using a dynamic schedule.

Motivation*:* In a multi-hop tracking environment, nodes that are far away from sink have to forward fewer packets and hence their lifetime is longer. Nodes that are closer to the sink have to forward more packets from the far off nodes. This leads to reduction in lifetime of the nearby nodes. Existing sleep planning protocols for target tracking are not specifically designed to balance the lifetime of all the nodes. We propose a novel protocol (ELS) that balances the lifetime of the interior nodes and removes the hotspot near the sink in the tracking state by providing an adaptive sleep schedule for the radios. Our schedule reduces the energy consumption without affecting the sensors' activities.

3. ELS Protocol

In target tracking applications, the target enters in the border region and moves randomly in the environment. Sensing information has to be communicated to the sink only during the target's presence. We exploit the above feature to design an effective sleep schedule for target tracking sensor networks that increases the network lifetime and reduces the end-to-end latency. Our ELS protocol is designed to have two types of sleep planning to suit the above condition. It follows a (1) *static sleep schedule* when there is no target (surveillance state) and (2) *dynamic sleep schedule* when there is target (tracking state). In ELS, the radio of border layer nodes is always 'on' to communicate with the interior layers whenever a target enters the monitoring area. Interior nodes transfer the data packets only when they are informed by their neighbors that a target is found. As interior nodes have higher energy consumption due to data forwarding, they are allowed to sleep more during the surveillance state. This kind of sleep schedule conserves energy in the surveillance state and tracks the target by dynamically changing the schedule in the tracking state. Table1 shows the notations used in our protocol.

Table 1 Notations

n	Number of layers of interior nodes
T_{on}	Radio listen time at periodic 'on' slot
T_{sleep}	Sleep time in between 2 'on' slots
T_{total}	Total lifetime of the network
T_{max}	Maximum sleep time between two consecutive 'on' slots
E_{listen}	Energy consumed in listen mode of radio per 'on' state
E_{tx}	Energy consumed in transfer mode of radio per packet
K	No. of packets transmitted by a node
N_f	No. of nodes that send packets to a given interior node for forwarding
E_{border}	Energy consumed by a border node
$E_{interior}$	Energy consumed by an interior node
R	Coverage radius of a node
S	Maximum speed of target
h	Hop distance of a node from sink

Assumptions: In our protocol, all the nodes are considered to be homogeneous and static. Nodes in the network are GPS equipped or use localization algorithms, so that information about the node's position is used to find the exact trajectory of the target using target tracking methods[3], [4], [5], [18], [19]. Targets that enter through the boundary in a 2-dimensional terrain space can be tracked. Target speed should be low. The sink can be located either in the center or on one side of the boundary depending upon the application.

3.1 Static Sleep Schedule

In our paper, sensor nodes are categorized as border nodes and interior nodes and they are operated in layers. The top two layers are kept as Border layers and the rest are Interior layers. The border nodes (sensing and radio) are kept alert all the time, in order to detect the target. The border nodes may die out quickly if they are active all the time. Hence, we keep two or three layer of border nodes which are made active at different time intervals such that one layer is active to sense any target. The active layer of border nodes will communicate with the interior layers if a target is detected. The number of layers can be chosen based on the network details. Interior nodes follow a sleep schedule that is different from that of the border nodes to conserve power. The radios of the interior nodes are 'on' only at short specific intervals. Interior nodes communicate to the sink only when a target's arrival message is received.

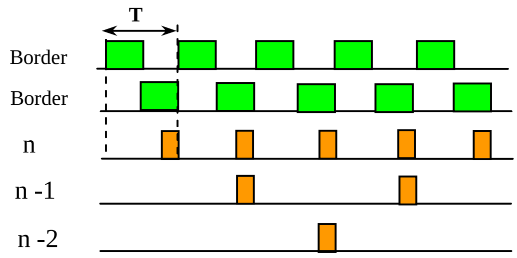


Fig.1 Static Sleep schedule for radios of nodes

Figure 1 shows the proposed sleep schedule during the surveillance state. We assume there are two layers of border nodes and 'n' interior layers. A unit time T is divided into two slots T_{on} and T_{sleep}. The interior nodes will be active during T_{on} and sleep during T_{sleep}. The nodes in layer 'n' will wakeup once in every one unit of time. The nodes in layer 'n-1' will wakeup once in every two units of time. The nodes in layer 'n-2' will wakeup once in every three units of time and so on. The effectiveness of this sleep schedule is nodes that are nearer to the sink are given the chance to sleep more when compared to nodes that are far away. The key idea is though the interior nodes have longer sleep time, they can receive the target's arrival message in time as the target takes some time to reach the interior nodes.

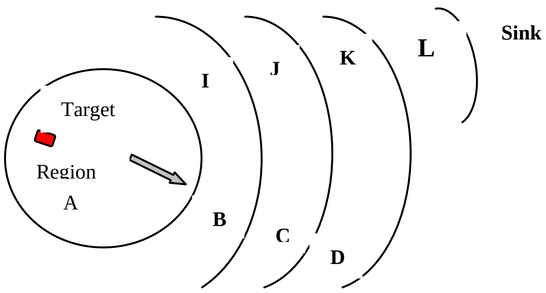


Fig.2 Target movement from region A and next hop Neighborhood

Balancing the Lifetime of the Nodes:

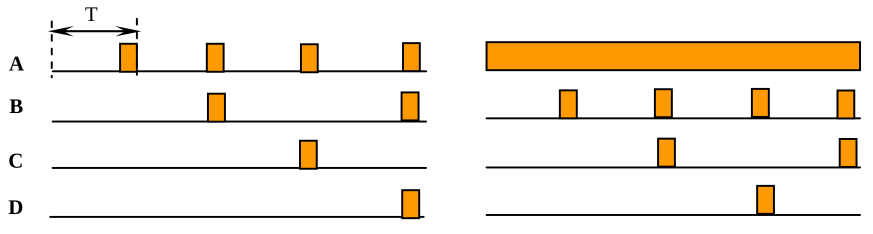
In target tracking, interior nodes that are nearer to the sink will be forwarding a lot of data packets from the border nodes. If a target arrives, the interior nodes handle more traffic when compared with that of the border nodes because of their data-forwarding task. This leads to decrease in the lifetime of the interior nodes. On the other hand, the border nodes will have higher lifetime, because of less forwarding overhead. Hence there is a need to balance the lifetime of border nodes and interior nodes so that the overall network lifetime increases. As per our static schedule, border nodes are always 'on' to detect the target and they have higher radio energy consumption to compensate their lower packet transmission. The interior nodes sleep more and they have lower radio energy consumption to compensate their higher packet transmission.

3.2 Dynamic Sleep Schedule

Whenever there is no target, the communication modules of the interior nodes are put into sleep. Though the sleep schedule saves energy, it may lead to missing of event detection as there are possibilities that they might not be alert when a target arrives. So the schedule of the radios is changed dynamically during the arrival of a target in order to detect the targets faster. This kind of energy saving does not affect tracking due to latency.

A target should be tracked with spatial and temporal precision. Whenever a target enters the network, control packets are transmitted periodically from the sensing node to its neighbor nodes to make them active as long as the target is present in that area. Data packets are sent periodically as long as the target is detected in that area. As the target moves, the corresponding neighbor nodes are informed to be alert because they should be able to sense before the target reaches that position. When a target is identified, the one hop neighbors in that region are made active immediately. Then the 2nd, 3rd hop neighbors in that region are informed to change their sleep schedule. The number of hops is chosen based on target speed. The nodes reduce the sleep interval by adding additional 'on' time slots.

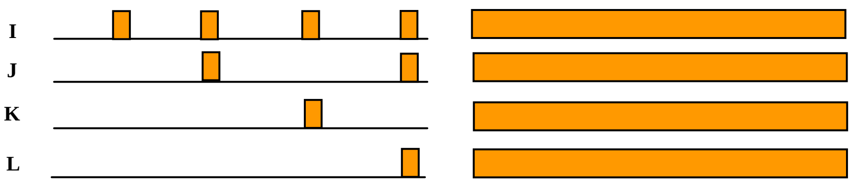
Target Trajectory:
Assume the target is currently moving in Region A as shown in Figure 2. Let the predicted path of target movement is B, C, D. The one hop neighbors in Region B, two hop neighbors in Region C and three hop neighbors in Region D change their schedule dynamically. As the target moves, the path is activated dynamically by sending the control packets to the neighbors. Figure 3 shows the old and new sleep schedule of the neighboring nodes as the target moves from region A towards region D.



a. Schedule before target arrives in region A **b. Schedule when target moves from A to D**

Fig.3 Dynamic sleep Schedule of the nodes in the path of Target movement

Target to Sink Path:
When a target enters the network, details of the target should be sent to the sink continuously to track the target. As shown in Figure 2, let (I, J, K, L) be the shortest path between the current target location A and the sink. The intermediate nodes in this path are activated by changing their radio schedule using the control packets. This activation helps to reduce the latency for transmitting data to the sink. Figure 4 shows how the radio schedule is dynamically changed. All the intermediate nodes in the neighborhood are kept active for a particular period of time based on the target's speed. When the timer expires, nodes follow their usual schedule.



a. Schedule before target arrives in region A **b. Schedule after target arrives in A**

Fig. 4 Dynamic sleep Schedule of intermediate nodes in the Target to sink path

4. Theoretical Analysis

In this section, we analyze the sleep schedule in our protocol and theoretically show how the lifetime of the interior nodes is increased to improve the overall network lifetime in target tracking applications.

Static Schedule:
In the surveillance state, interior nodes are allowed to sleep as per the static schedule. Let R be the coverage radius of a node and S be the maximum speed of target. The maximum sleep time, T_{max} is calculated based on the hop distance. T_{max} of an interior node at n^{th} hop is given by n*R/S. T_{max} of the nodes at various hops is found as per Table 2.

Table 2 Maximum Sleep time

Node location	T_{max}
Node is 1-hop away from border node	R/S
Node is 2-hops away from border node	2R/S
……………….	……
Node is n hops away from border node	(n)R/S

Dynamic Schedule:
When a target arrives, the sleeping interior nodes should be activated before the target enters in that region because tracking should not fail due to late alert message. Hence, the number of hops to be activated prior should be identified before the target enters into that region. T_{max} of an interior node at hop length 'h' is chosen as follows.

$$T_{max} < R/S * h \quad (1)$$

Hence, we find the number of hops to be activated prior 'H' as,

$$H > T_{max} * S/ R \quad (2)$$

Balancing Lifetime:
In tracking state, interior nodes near the sink will be forwarding more data packets from the exterior layers which lead to decrease in their lifetime. Hence there is a need to balance the energy consumption interior nodes with that of border nodes. Each sensor node consists of sensing, computing, and communicating modules. In order to conserve power, energy consumption by communication can be reduced by periodically making the radio off using appropriate sleep schedule. We find the energy consumption of the border and interior node in the tracking state as per the notations listed in Table 1. When there is no target, the energy consumption of a node is given by,

$$T_{total}/(T_{sleep} + T_{on}) * E_{listen} \quad (3)$$

When data packets are transmitted, the energy consumption of a node is given by,

$$[T_{total}/(T_{sleep} + T_{on}) * E_{listen}] + [K * E_{tx}] \quad (4)$$

In S-MAC:
Both the border and interior node will be sleeping for the same time i.e., their T_{sleep} is same. When there is no target, energy consumption of all the nodes is same.

$$E_{border} = E_{interior} = [T_{total}/(T_{sleep} + T_{on}) * E_{listen}] \quad (5)$$

When a target is present, the energy consumption of the border node and interior node is given by

$$E_{interior} = [T_{total}/(T_{sleep} + T_{on}) * E_{listen}] + [\mathbf{N}_f * K * E_{tx}] \quad (6)$$

$$E_{border} = [T_{total}/(T_{sleep} + T_{on}) * E_{listen}] + [K * E_{tx}] \quad (7)$$

In S-MAC, $E_{interior} > E_{border}$ as the interior node have to forward the packets from their exterior neighbors to the sink. Hence, interior node drains off its energy soon which leads to lesser lifetime of the network.

In ELS:
Imbalance of energy consumption in interior node due to data forwarding with respect to border node is compensated. In the *surveillance state*, sleep time of the interior node is varied as per its hop distance and it is adjusted based on T_{max}. Its $E_{interior}$ is given by

$$E_{interior} = [T_{total}/ (T_{max} + T_{on}) * E_{listen}] \quad (8)$$

$$E_{border} = [T_{total} /(T_{sleep} + T_{on}) * E_{listen}] \quad (9)$$

In ELS, $E_{interior} < E_{border}$ and the interior nodes are made to have lower energy consumption by making them sleep more. In the *tracking state*, interior node has higher energy consumption due to packet forwarding, compared to border node. So,

$$E_{interior} = [T_{total}/ (T_{max} + T_{on}) * E_{listen}] + [\mathbf{N}_f * K * E_{tx}] \quad (10)$$

$$E_{border} = [T_{total} /(T_{sleep} + T_{on}) * E_{listen}] + [K * E_{tx}] \quad (11)$$

However, the energy consumption of interior node is balanced by using more sleep time. Border node has lower energy consumption due to data forwarding and this helps us to keep it alert to detect target entry. This leads ELS to achieve maximum lifetime without missing any target. Though E_{border} and $E_{interior}$ are not exactly equal, this brings out a balance in energy consumption of border and interior node. As per the analysis, we show that ELS increases the lifetime of the network more than S-MAC.

5. Simulation Results

The performance of ELS is evaluated using the GloMoSim [17] discrete event simulator. The parameters used in our simulation are listed in Table 3. The terrain area is 1000m x 1000m with a uniform distribution of 121 nodes. The target enters the field at a random location through the boundary and moves at a constant speed. Border nodes at 11th hop are always on and the sleep time increases as the hop length decreases. Table 4 shows the periodicity of the active time period in ELS schedule. The bandwidth is set as 10 Kbps. The simulation setup is run several times when there is no target and when there is a target with different amounts of network traffic. We compare the performance of ELS with 2 other protocols, namely (1) 802.11 DCF (nodes are always 'on') (2) S-MAC (all the nodes are 'on' for every 4 sec period).802.11 DCF is used as a baseline. We use S-MAC, a standard contention-based protocol to provide a meaningful comparison.

Table 3 Simulation parameters

Parameter	Value
Transmitting power	14 mw
Receiving power	13 mw
Power consumption in idle mode	12 mw
Power consumption in sleep mode	0.0016 mw
Packet size	64 bytes
Max speed of the vehicle	15 m/s
Transmission range (radio)	120 meters
Sensing range	60 meters

5.1 Energy Consumption

Energy consumption of the nodes is analyzed for S-MAC and ELS protocols in the surveillance and tracking state. We refer energy consumption as average energy consumption of a node at a particular hop length. The performance of ELS in the tracking state is analyzed by varying the data traffic from 50 to 500 packets.

Table 4 Radio schedule

Hop length from sink	T_{active} for every	Hop length from sink	T_{active} for every
1	40 sec	6	20 sec
2	36 sec	7	16 sec
3	32 sec	8	12 sec
4	28 sec	9	8 sec
5	24 sec	10	4 sec

(a) In Surveillance State

Figure 5 shows the energy consumption when there is no target. S-MAC consumes same amount of energy at all hop lengths as the sleep period is same for all the nodes. However, in ELS protocol, interior nodes consume less energy because of the static radio schedule where they are allowed to sleep longer. ELS saves approximately 85% more energy when compared to S-MAC when hop length is less.

(b) In Tracking State

The energy consumption for different amounts of data traffic is obtained in the tracking state. Figure 6 shows the energy consumption at different hop lengths when 50 packets are transmitted by different sensor nodes. Figure 7 shows the results when data traffic is 200 packets. Figure 8 shows the results when 500 packets are generated at different sensor nodes and transmitted. Energy consumption of nodes at larger hop length is same irrespective of the data traffic as they have to forward fewer packets. When the data traffic increases from 50 to 500 packets, interior nodes consume more energy due to more packet forwarding. In S-MAC, interior nodes consume more energy because the sleep time for all the nodes is same. ELS protocol follows a dynamic sleep schedule by activating the neighbor nodes only during the presence of the target. When hop length is less, the number of packets to be forwarded is more. But the interior nodes are allowed to sleep more, and hence total energy consumption (radio + packet forwarding) is balanced. When compared to S-MAC, ELS saves approximately 75% more energy when the data traffic is 50 packets, saves nearly 60 % of energy when the traffic is 200 packets, saves 50% of energy when the data traffic is 500 packets. Adaptive sleep schedule enables ELS protocol to achieve low energy consumption.

(c) Network Lifetime

Figure 9 shows the network lifetime obtained by the 3 protocols based on the energy consumption for different amounts of packet traffic. We assume the initial energy of a node as 36000 mWsec. In 802.11 DCF, network lifetime is lower as its energy consumption is always high as it has no sleep period.

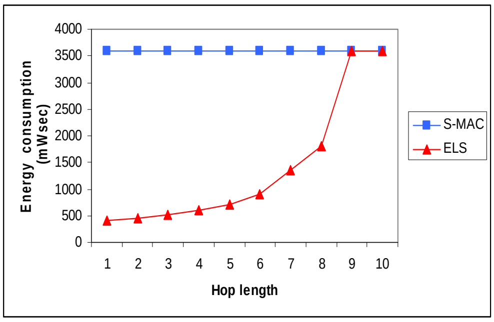


Fig.5 Energy consumption when there is no target

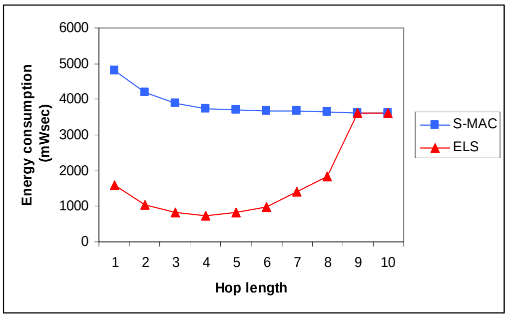


Fig. 6 Energy consumption for Low Traffic

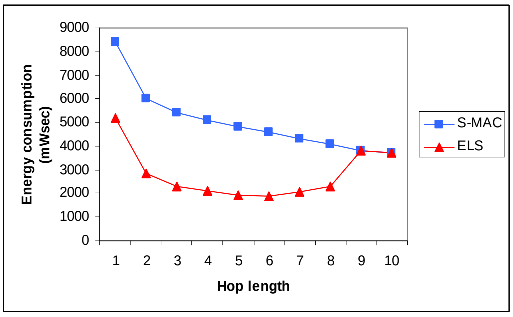


Fig.7 Energy consumption for Medium Traffic

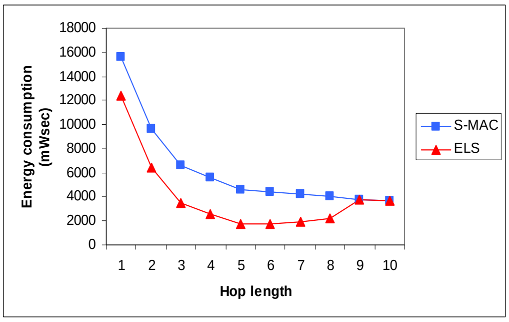


Fig. 8 Energy consumption for High Traffic

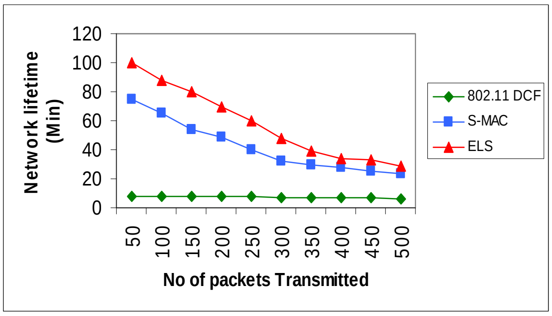


Fig. 9 Network lifetime Vs Packet Traffic

S-MAC performs better than 802.11 due to its periodic sleep in all nodes. Our ELS provides more network lifetime and performs much better than other two protocols by balancing the energy consumption of all the nodes. In particular, ELS provides 25% more lifetime than S-MAC, at low load.

5.2 End -to-End Latency

(a) Effect of Target Speed

As shown in Figure 10, we find the end-to-end latency for different target speeds. We assume the average hop length between the target and sink is 5. In case of 802.11 DCF, latency remains constant and is less than other protocols, since the radio is always on. In S-MAC, latency is high due to the waiting time while forwarding packets through the intermediate nodes. Latency remains constant even when the speed varies as it follows a periodic on. In case of ELS protocol, we reduce the latency at low target speed by our dynamic schedule. As the target speed increases, the dynamic schedule could not activate the radios in that path faster. Since the activation of the path takes some time, waiting time affects the latency as the target speed increases. However, ELS is better than S-MAC and decreases the latency by 50% at low speed.

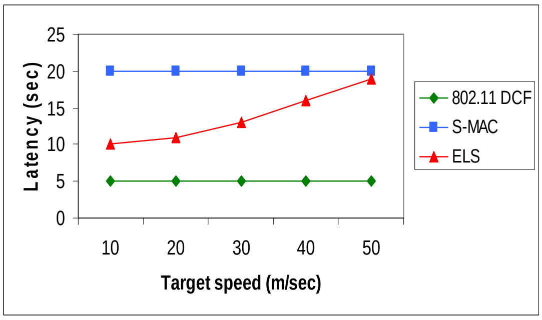


Fig.10 Latency for different Target speeds

(b) Effect of Hop Length

As hop length increases, end-to-end latency also increases for all the protocols. We fix the target speed as 20 m/s. As shown in Figure 11, we vary hop length between the target and sink and analyze its effect on end-to-end latency. Since 802.11 DCF does not have any sleep time, latency is less than that of other protocols. In case of S-MAC, the periodic sleep affects the latency directly and the waiting time at intermediate nodes while forwarding packets increases the latency as hop length increases. In case of ELS protocol, we reduce the latency by 50% compared to S-MAC by activating the radio schedule in the 'target to sink' path.

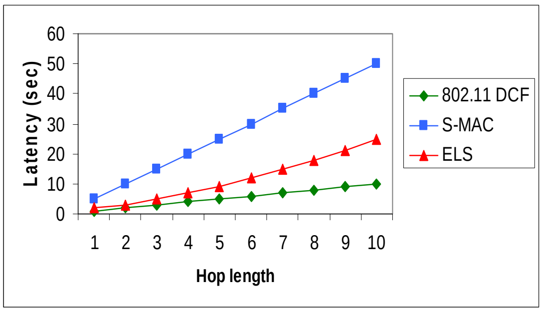


Fig.11 Latency for various Hop lengths

6. Conclusion

In this paper, we proposed a new Energy Efficient Sleep Schedule (ELS) to increase the lifetime of Target Tracking Sensor Networks. Our sleep schedule consumes less energy by allowing interior nodes to sleep for longer duration in the surveillance state and tracks the target with low latency by dynamically changing the schedule along the target-to-sink path in the tracking state. Higher energy consumption in interior nodes due to data forwarding is balanced to increase the network lifetime. Simulation results showed that ELS protocol performs better than S-MAC and 802.11 DCF protocols with respect to network lifetime. When compared to S-MAC, ELS increases the network lifetime by 25% at low data traffic and reduces the latency by 50%.

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N.A.Vasanthi received the B.E degree in ICE and M.E. degree in CSE from Bharathiar University, Coimbatore, India. She is currently doing research on Wireless Sensor Networks at Anna University. She is working as an Assistant professor in the Department of Information Technology in Sri Krishna College of Engineering and Technology, Coimbatore. She is a life member of CSI and ISTE. Her area of interest is Wireless Networks, Pervasive Computing and Soft Computing.

S. Annadurai is currently the Principal of Government College of Technology, Coimbatore, India. He did his B.E.(ECE) and M.E.(PS) degrees at Madras University, M.E.(CSE) at Bharathiyar University and Ph.D at Anna University. He is a life member of CSI and ISTE. He has contributed more than hundred research papers in different areas of Computer Science and Engineering such as Pattern Recognition, Neural & Fuzzy Neural Networks, Image Processing and Computer Networks.