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RESEARCH ARTICLE

SMLMAC-HEAP: Slotted Multi-Layer MAC Protocol for Wireless Sensor Networks Powered by Ambient Energy Harvesting

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Abstract

Objectives: To study the lifetime of Wireless Sensor Network (WSN) as well as to propose and simulate a suitable approach so that the Quality-of-Service (QoS) of the network in terms of throughput improved when compared with the previous methods. **Methods:** The lifetime of WSN depends on the MAC layer because energy consumption is more due to the sharing access of media. Our approach is designed not only to adopt the division of the MAC layer into a number of slots by keeping both listen and sleep mode but also using the solar harvested energy; hence, the network's lifetime is improved with the compared protocol. Our approach with compared protocol is simulated through MATLAB simulator on EZ430-RF2500-SHE" (Datasheet of Texas Instruments'). **Findings:** In WSN, we found that energy consumption is more at the MAC layer, so network performance degrades in terms of lifetime. To solve the issue of energy consumption in WSN, researchers focused on and designed several techniques to improve the MAC layer. To bring out the practicality of the proposed protocol, we present a case study on the variation of layers with slots in terms of throughput metrics. Finally, the simulation result shows that the proposed protocol performs better than MLMAC-HEAP, Probabilistic Polling and Optimal Polling from layer 7 with slot 7. **Novelty:** The proposed approach merges the two concepts; one is by using the ambient solar energy, and the other, by adopting slot concepts for each layer of MAC.

Keywords: MAC; MLMAC; MLMAC-HEAP; WSN

1 Introduction

Wireless Sensor Networks (WSN) are mostly battery powered means limited capacity and cannot be reenergized because of its deployment in harsh and dynamic environment. To overcome the limitation of battery-powered environment, Energy Harvesting (EH) techniques evolved(1). Researcher use solar power for energy harvesting, as solar energy is easily available and a convenient source(2). The efficiency may decrease on cloudy days. Author proposed electromagnetic harvesting technique for energy based on electromagnetic induction(3). Due to the magnetic flux around the inductor, electromotive force is generated. The used of inductor generates sufficient amount of energy to feed into WSN applications. Author proposed a new multi-layer-based MAC protocol (MLMAC-HEAP) with the concept of solar energy(4). Here nodes are unsynchronized i.e. as soon as they sense the data; they forward it without waiting for other nodes. This minimizes the delay caused by waiting for other nodes to send data. The major problem here is communication overhead caused by unsynchronized data transmission.

Motivated by these facts, we have designed a proposal, which adopts the harvested energy along with new variants of MAC protocol for enhancing the network lifetime and throughput of network. For better result, our proposed proposal follows the ambient energy and variants of MAC layer. The main contribution of this paper is as follows:

a. This work utilizes the concept of solar ambient energy for increasing the lifetime of
WSN than battery-powered (limited capacity).

b. There are L levels that do not overlap in listening. The listen times of nodes at various tiers do not therefore cross over. A node only awakens in the layer it is allocated. In our proposal, we propose to divide the listen schedule into L non-overlapping layers, each of which is separated into two slotted pieces, such as listen and sleep.

In this paper, our proposed protocol SMLMACHEAP adopts the slot duration period and collects the harvesting energy from solar. Proper distribution of slot period in non-overlapping layer decreases the chances of packet loss, idle mode and collision of the network. Hence, it increases throughput when compared with the existing protocols.

2 Material and methods

This section introduces the Slotted Multi-Layer MAC protocol. Powered by Ambient Energy Harvesting (SMLMAC-HEAP), which comes with a thorough explanation, flowchart, and algorithm proposal.

2.1 Brief Description of Proposed Protocol (SMLMAC-HEAP)

The fact that Wireless Sensor Networks (WSNs) are often battery-operated makes it even harder to manage energy use. Since energy consumption is most in MAC Layer [5, 6], an efficient design of MAC Layer protocol will save energy of nodes thereby increasing network lifetime in turn QoS. For this reason, experts are developing fresh methods to improve the MAC Protocol in order to boost the MAC layer's performance.Recent improvements in MAC protocols allow wireless sensor network powered by ambient energy harvesting (WSN-HEAP) to be a great choice in comparison to battery-powered networks(4–7). Presently research shows(8–13) that use of ambient energy like solar, wind, water, Radio Frequency (RF) etc. concept adopted by WSN outperforms than battery-powered.

SMLMAC-HEAP is therefore created by applying the idea of optimal slot period distribution to non-overlapping MAC layers while also using solar ambient energy. Each slot period has two schedules, namely listen and sleep, which are connected to each frame. Layers L of the listen schedule are non-overlapping. As indicated in Figure 1, each layer is further separated into two slotted portions. Nodes are scattered among the slotted part of each layer, following the listen/sleep schedule in each slotted part. Therefore, the listen schedules of the nodes in slotted part are non-overlapping. A node wakes up only at its allocated slot according to our proposed protocol SMLMAC-HEAP. Sensor nodes, which have less energy than energy neutrality condition (ENC) value can go to sleep mode for intake of ambient energy, in this case solar.

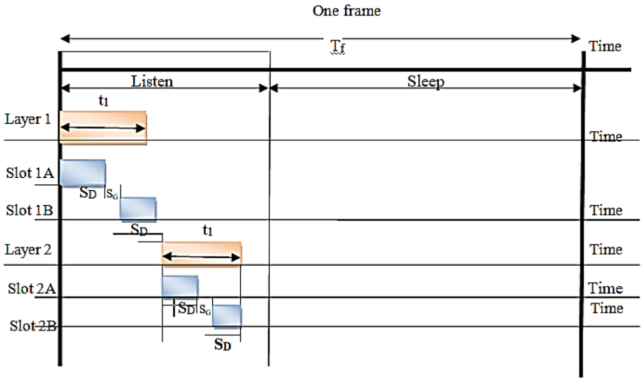

Fig 1. Timing Parameters of one frame for SlottedML-MAC

SMLMAC-HEAP has been compared with existing protocols like MLMAC-HEAP proposed by Kochhar et al. [4], Probabilistic Polling by ZA Eu and HP Tan(14) and Optimal Polling by A. A. Rescigno(15). MLMAC-HEAP uses only layer concepts (1, 2, 3, 4, and so on) to the listen period of each frame without slots whereas SMLMAC-HEAP has added the number of slots (1, 2, 3,4 and so on) into the listen period of each layer in one frame. On the other hand, Probabilistic Polling and Optimal Polling have only concentrated on increasing the lifetime of network with a single layer in a battery-powered network.

Figure 2 provides a flowchart that illustrates the general operation of SMLMAC-HEAP. The flowchart's step-by-step thorough description is as follows:

- At the beginning, nodes are in sleep state. After they wake up, they need sufficient energy for any operation, so they go to power management (PM) state.
- The layers are created and divided into number of slots where each slot consists of listen and sleep period. According to the predefined model, traffics are created and distributed. Nodes are uniformly and randomly scattered among the layers with number of assigned slots.
- Node enters into the transmit state only if its energy level is equal or above the threshold value of Energy Neutrality Condition (ENC) else the node goes back to sleep state to intake the harvested energy from solar. This process continues until the energy condition is fulfilled for entering into the transmit state.
- The nodes entering into transmit state are again checked whether they have any data to send or not. If yes, node checks channel availability by sending "Hello" messages. After getting acknowledgement from the recipient within a timeout period, data communication is established in the network. When the communication starts, it follows the slotted concept, which is added with the multi-layer of each frame duration.
- If the acknowledgement is not received by the node within a timeout period (Back-off algorithm), it indicates the channel is busy and node again enter into the energy neutrality condition and process repeats.

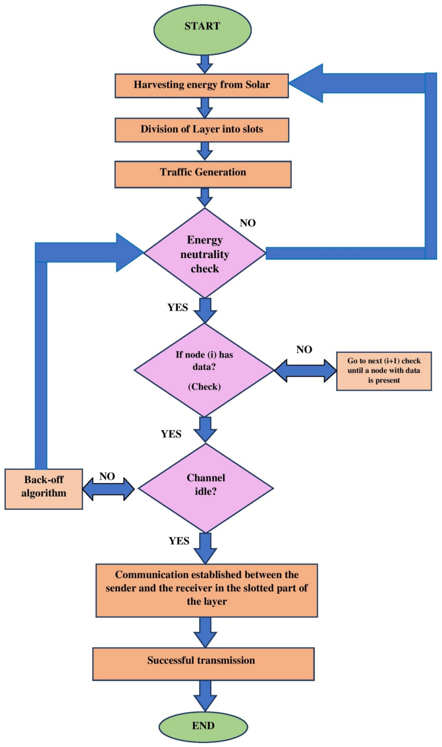

Fig 2. Working Principle of SMLMAC-HEAP

2.2 Notation

The following notations have been used throughout this paper.

Table 1. Design Parameters

Notation	Description
T_f	Frame duration
T_R	Maximum response time
t_1	Listening period for one layer
L	Number of layers
N_f	Number of frames
T_D	Total time delay
T_N	Network life time
E_H	Average energy harvesting rate
S_D	Slot duration per layer
S_N	Number of slots
S_G	Guard time between the layers
λ_{avg}	Average traffic generated
P	Average node power Consumption
P_{CT}	Power consumed per unit time
V	Voltage
E_{tx}	Transmission energy
E_{rx}	Data reception energy
E_C	Total consumed energy
I_{tx}	Transmission current
I_{rx}	Data reception current
N	Number of nodes
P_{tx}	Power of the transmitter
P_{rx}	Power of the receiver
$T_{sensing}$	Sensing time
$T_{processing}$	Processing time
T_{pm}	Power management time
$T_{standby}$	Standby time
T_{tx}	Transmission time
T_{ta}	Turn-around time
ρ	Average node power consumption
n	Number of nodes

Proposed Algorithm Slotted ML-MAC HEAP works in six different steps. Design parameters required to express this work and purpose listed in Table 1.

Step 1: [Compute the frame duration (T_f)]:

T_f is bounded by the maximum response time delay T_R and total listening time of all the layers.

$$T_f \leq T_R \tag{1}$$

$$T_f > t_1 \times L \tag{2}$$

The number of frames N_f is bounded by:

$$\frac{T_N}{T_R} \leq N_f < \frac{T_N}{t_1 \times L} \tag{3}$$

Step 2: [Compute the total time delay ($\mathbf{T_D}$)]:

$$T_D = T_{sensing} + T_{processing} + T_{pm} + T_{standby} + T_{tx} + T_{ta} \tag{4}$$

Step 3: [Calculating the Network life time ($\mathbf{T_N}$)]:

Network life time is calculated from the following equation:

$$T_N = \frac{E_H}{P_{CT}} \tag{5}$$

Step 4: [Compute slot duration per layer S$_D$ and estimate number of slot S$_N$]:

The duration of two slotted part of each layer is governed by the active time of each layer and is given as:

$$t_1 > S_D \times S_N \qquad (6)$$

From equation (3) and equation (6), it is bounded as:

$$S_D \leq \frac{T_N}{N_f \times S_N} \qquad (7)$$

The listening time of each layer should be followed by:

$$S_N\left(S_D + S_G\right) \leq t_1 \qquad (8)$$

Therefore, the number of slots is governed by:

$$S_N \leq \frac{t_1}{\left(S_D + S_G\right)} \qquad (9)$$

The number of slots is counted from equation (9).

Step 5: [Compute the listening period per layer t$_1$)

The listening period of one-layer t$_1$ is governed by the ambient harvesting energy E$_H$ and the average node power consumption ρ:

$$\rho \times t_1 \times N_f \leq E_H \qquad (10)$$

t_1 is bounded as:

$$t_1 \leq \frac{E_H}{\rho \times N_f} \qquad (11)$$

According to equation (6) and (11)

$$S_D \times S_N \leq \frac{E_H}{\rho \times N_f} \qquad (12)$$

As we know, t_1 is bounded with time needed to send at least one packet, which is given by following equation:

$$t_1 > T_D \qquad (13)$$

Thus from equation (11) and (13), t$_1$ is bounded as:

$$T_D < t_1 \leq \frac{E_H}{\rho \times N_f} \qquad (14)$$

Step 6: [Compute the no. of layers (L)]

Before going to compute the number of layers, λ_{avg} (average traffic generated per frame) is required and that is calculated by equation (15).

$$\lambda_{avg} = n \times \lambda \times T_f \qquad (15)$$

Then,

$$L \times S_N \times S_D > \lambda_{avg} \times T_D \qquad (16)$$

So that, according to equation (16), L is bounded:

$$L \geq \frac{\lambda_{avg} \times T_D}{S_N \times S_D} \qquad (17)$$

However, S$_G$ is the guard time between the layers. As a result, the upper limit of L is:

$$L\left(t_1 + S_G\right) \leq T_f$$

Using equation (17) and (18), L should follow the below design bounds:

$$\frac{\lambda_{avg} \times T_D}{S_N \times S_D} \leq L \leq \frac{T_f}{t_1 + S_G} \qquad (19)$$

2.3 Traffic Mechanism

Traffic mechanism helps to manage and estimate the proper utilization of resources for nodes. It can also give a solution to energy constraint of the network lifetime. Probability Density Function (PDF) purely depends on different parameters like location (a), shape (b) and scale(c). Traffic mechanism follows with distribution of traffic called as variable and that variable is directly related with parameters. In some traffic distributions, the rate parameter (λ) is used instead of the scale parameter (c). The reciprocal of the scale is rate. The evaluation of parameters is calculated by using the following equation 20, 21 and 22 respectively.

$$a = \frac{l}{\beta} \qquad (20)$$

$$b = \frac{\beta\lambda}{l(\beta-\lambda)} \qquad (21)$$

$$c = \frac{1}{\lambda} \qquad (22)$$

Where,

l - Average packet length

λ - Average data rate

β - Maximum burst rate

Proposed protocol SMLMAC-HEAP along with other comparison protocols are simulated under Poisson Distribution Traffic model. The Probability Density Function (PDF) of Poisson model is given below:

$$f(t) = be^{-b(t-a)} \qquad (23)$$

Due to the combination of light and independent traffic, we have chosen Poisson distribution.

2.4 Energy Harvesting Analysis

Nodes in the network follow the different stages like sleep, listen, processing, sensing, transmitting etc. Each stage consumes some energy.

Equations 24 to 27 are used to calculate nodes' energy at different stages after using our proposed protocol SMLMAC-HEAP.

$$E_{tx} = P_{tx}T_{tx} = I_{tx}VT_{tx} \qquad (24)$$

$E_{rx} = P_{rx}T_{rx} = I_{rx}VT_{rx}$ (25)

$E_C = P_{rx}T_{rx} + P_{tx}T_{tx} + P_{sleep}T_{sleep} + P_{ta}T_{ta} + P_{standby}T_{standby} + P_{proc}T_{proc} + P_{sensing}T_{sensing} + P_{pm}T_{pm}$ (26)

$E_C = I_{tx}VT_{tx} + I_{rx}VT_{tx} + I_{sleep}VT_{sleep} + I_{ta}VT_{ta} + I_{standby}VT_{standby} + I_{proc}VT_{proc} + I_{sensing}VT_{sensing} + I_{pm}VT_{pm}$ (27)

Where,

E_C – Energy consumption

P_{rx}, P_{tx}, P_{sleep} –P_{ta} Total power consumed in receiving.

T_{rx} , T_{tx} , T_{sleep} – Total power consumed in transmitting.

$P_{standby}$, P_{proc} – Power consumed in standby state and processing of data.

$P_{sensing}$, – Power consumed in data sensing.

P_{pm} – Power consumed in power management state.

$T_{standby}$, T_{proc}, $T_{sensing}$ – Time spent by nodes in standby, processing, sensing respectively.

T_{pm} – Time spent by nodes in power management

T_{ta} – Turn-around time

3 Results and Discussion

This section is devoted on comparing SMLMAC-HEAP with other existing protocols like MLMAC-HEAP [**4**], Probabilistic Polling(14) and Optimal Polling(15). One of the most essential performance metrics for determining QoS of network is throughput. When the network's throughput improves, the overall performance of the network improves as well. Therefore, along with increase in battery life, throughput of the network has been taken as the major parameter and is calculated to improve Quality of Service of the network in this section**.** By applying our proposed method of slot period in the network with ambient energy concept, the result and analysis shows that throughput is increased and SMLMAC-HEAP performs better than existing protocols.

The proposed protocol SLMAC-HEAP is simulated using MATLAB Simulator. For the simulation and comparison purpose parameters used here are same as MLMAC-HEAP [**4**] and some are taken from "EZ430-RF2500-SHE" (Datasheet of Texas Instruments'). Table 2 shows about the simulation parameter with their values and units, which are used during simulation.

Table 2. Simulation Parameters

Simulation Parameters	**Values**
N	10–200
L	1–10
T_f	1 S
Layer duration	300/L Ms
P_{rx}	68.58 Mw
P_{sleep}	4.118 μw
P_{tx}	80.23 Mw
$P_{sensing}$	4.899 Mw
P_{proc}	5.68 Mw
$P_{standby}$	29.22 Mw
P_{ta}	71 Mw
P_{PM}	3.124 Mw
Λ	250 Kbps
L	100 Bytes
$T_{sensing}$	19.76 Ms
T_{proc}	61.4 μs/byte
$T_{standby}$	0.77 Ms
T_{ta}	196 μs
T_{PM}	6 Ms

3.1 Performance Metrics

By applying slot durations (1–10) to each layer, slotted MLMAC-HEAP is evaluated in terms of throughput (in Kbps). The amount of packets that are successfully received during a specific time period determines throughput.

$$Throughput = \frac{Number\ of\ packet\ received\ \times Packet\ size\ \times 8}{1000 * \ Simulation\ Period}$$

3.2 Simulation Results

This section presents an analysis in finding out the position (Layer number and slot number) where SMLMAC-HEAP outperforms than other compared protocols. By fixing the network size (n=100) i.e., constant with average energy E_H =10 mw, SMLMAC-HEAP is compared with other protocols like MLMAC-HEAP [4], Probabilistic Polling(14), Optimal Polling(15) and performance is measured in terms of the throughput. Then we divide the slot from 1 to 10 in each layer and calculate throughput to plot the graphs in the following section.

The graphical findings are displayed in tabular form for clear of understanding.

• From Table 3, we observe that, in Layer 6 with the slots like 8, 9 and 10, the performance of SMLMAC-HEAP in terms of throughput are 258.54Kbps, 265.52 Kbps and 269.58 Kbps respectively. MLMAC-HEAP with Layer 6 has a throughput of

Table 3. Throughput Analysis

Slot Layer	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	MLMA-CHEAP	Probabilistic Polling	Optimal Polling
L_1	31.5	34.5	37.52	40.9	45.6	51.2	62.7	71.5	75.4	78.7	67.2	102.83	258.35
L_2	46.5	52.7	59.8	68.1	79.2	97.8	110	122.2	132.4	147.2	108.7		
L_3	57.3	61.56	65.4	77.2	94.58	122.23	151.3	157.9	171.45	178.25	144.15		
L_4	60.5	72.5	82.28	104	132.12	162.56	183.5	191.5	203.45	213.65	181		
L_5	72.39	94.82	109.27	137.33	162	187.51	225.25	234.56	239.1	243.25	219.25		
L_6	91.25	107.23	129	159.1	181.89	224.26	256.56	258.54	265.52	269.58	253.35		
L_7	101.2	119	153.32	172.67	213.29	247.8	314.56	335.35	347.46	353.68	292.38		
L_8	121.29	157.59	183.37	216.24	259	298.97	356.87	368.82	378	389.98	343.25		
L_9	149.36	193.27	219.23	247.49	278.97	315.45	367.67	379.87	393.93	406.39	357.37		
L_{10}	171.96	227.27	259.95	301.13	354	403.57	419.5	427.17	439.39	458.52	412.54		

253.35 Kbps, whereas Probabilistic polling and optimal poling have 102.83 Kbps and 258.53Kbps. As a result, SMLMAC-HEAP has received a greater number of packets than the compared existing protocols.

- Again, as seen from the tabular results the throughput from Layer 7 with slot 7 of SMLMAC-HEAP is 314.56 Kbps MLMAC-HEAP is 292.38 Kbps, Probabilistic polling is 102.83 Kbps and optimal polling is 258.53 Kbps. From the analysis, we conclude that SMLMAC-HEAP starts giving better throughput than other compared protocols in layer (L=7, 8, 9, 10) from slot (S_N =7).

By considering the above results, we chose SMLMAC-HEAP at (L=7, S_N =7) and compare with rest existing protocols MLMAC-HEAP [4], probabilistic polling(14), optimal polling(15) by varying the energy harvesting rate (mw) from 1 to 10. With increase in harvesting energy level, SMLMAC-HEAP (L=7, S_N =7) gives better throughput as compared to other protocols as seen from the Figure 3.

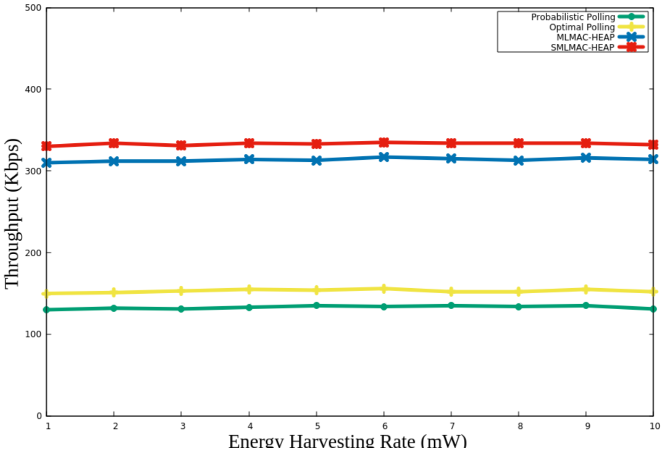

Fig 3. Energy Harvesting vs Throughput at L=7, S_N = 7 and n = 100

4 Conclusion

Quality-of-Service measures the performance of network. Network lifetime along with throughput is one of the important parameters in improving the QoS of a WSN. As these sensor nodes are battery-operated and cannot be recharged or replaced, energy needs to be conserved in order to increase the network lifetime. In Layer2 of the network model, MAC is the one of the most important protocols as it deals with all energy related parameters of nodes.

Here, we have proposed a new protocol (SMLMAC-HEAP) that combines the concept of slot duration to each layer of MAC, so that energy consumption be optimized and those sensor nodes, which has less energy than ENC value can go to sleep mode for intake of ambient energy from solar energy. All applications using wireless sensor networks can employ the proposed protocol because it is discovered to be straightforward, all encompassing, and effective. Based on simulation results, SMLMAC-HEAP is compared to existing protocols and is determined to perform better than existing protocols in terms of throughput and energy usage. SMLMAC-HEAP (L=7, S_N =7) gives better throughput as compared to other protocols as discussed in the above section.

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