An Energy-Aware Slotted ML-MAC Algorithm for Wireless Sensor Networks

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Abstract: A modified energy-aware slotted multi-layer medium access control (slotted ML-MAC) algorithm for wireless sensor networks is proposed in this paper. Slotted ML-MAC algorithm is designed to consume less energy and save power by positioning the radio in the low-power sleep routine. Sensor nodes in slotted ML-MAC algorithm have very short listening time than multi-layer MAC (ML-MAC) and sensor-MAC (S-MAC) which would minimize the energy required to interface with other nodes. Also, the number of collisions where two or more nodes try to send at the same time is reduced in Slotted ML-MAC. Simulation results of Slotted ML-MAC show much better performance compared with ML-MAC and S-MAC.

Keywords: Energy consumption, Medium access control (MAC), Wireless sensor networks (WSNs).

I. INTRODUCTION

The methodical and systematic use of energy is an important stage to prolong the network lifetime of wireless sensor networks, as most sensor nodes are battery operated and normally nodes cannot be recharged due to its deployment in harsh and remote environment [1]-[3]. Slotted ML-MAC is a contention based algorithms, which use an active/sleep routine frame to save energy consumption. In Slotted ML-MAC algorithm the listen period of a frame is divided into number of layers and again each layer is divided into two slot parts. In the active/sleep cycle strategies, sensor nodes recurrently turn off their radio and go into sleep routine, which will minimize the idle listening magnificently [4]-[9]. The frame length T_{frame} comprises of the listen and the sleep routine. It describe the duty cycle as T_{listen} / T_{frame} , T_{listen} is the active/listen time of a cycle.

Slotted ML-MAC is a self-organizing MAC algorithm and a distributed contention-based MAC algorithm where nodes discover their neighbors based on their radio signal level. It saves energy to re-send the falsified packets. The objective of the paper is to compare the performance and the energy consumption between three algorithms, i.e., S-MAC, ML-MAC and slotted ML-MAC.

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II. MAC ALGORITHMS IN WSNS

A.*S-MAC*: Sensor-MAC algorithm is the periodic synchronizations between sleep and listen schedule. Network time is divided into number of frames in time scale and each frame has active and sleep schedule is shown in Figure 1. The advantage of S-MAC is that the sleep schedules minimize energy to some extent. It avoids collision by using carrier sensing. Its implementation is simple. Moreover, synchronization packets update the listen-sleep schedules, which help to achieve better throughput. The latency is minimized among the nodes close to each other. The main disadvantage of S-MAC is that the node has to follow two different schedules. It results in more energy consumption also extra listening and overhearing. The latency and throughput increase as the neighboring nodes have their own sleep-listen schedules [10]-[11]. The sleep-listen schedules are predefined, which decreases the efficient of the algorithm under variable traffic load.

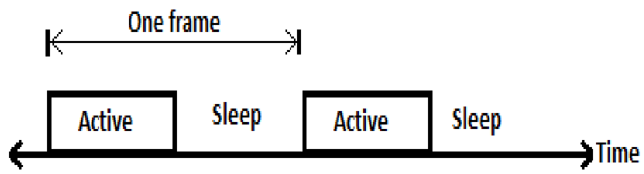

Fig. 1: The periodic listen and sleep in S-MAC

Based on the wireless local networks IEEE 802.11 distributed coordination function (DCF) MAC algorithm, researchers have proposed many MAC schemes for WSN. MAC algorithms can be classified into two types depending on the way the access is being controlled: Reservation based and contention based. In reservation-based MAC algorithms, the channel is reserved for nodes for a certain amount of time. Reservation-based MAC algorithms have many drawbacks like coordination to allocate and maintain the reservation slots, clock synchronization and lack of scalability that make them difficult to implement for wireless sensor networks.

B. *ML-MAC* : A multi-layer MAC (ML-MAC) algorithm is a distributed contention-based MAC algorithm where nodes discover their neighbors based on their radio signal level [12]. It is also self-organizing MAC algorithm that does not require a central node to control the operation of the nodes. The time in ML-MAC is split into frames and each frame is split into two periods: listen and sleep which is shown in Figure 2. The active period is sub-split into L non overlapping layers. Nodes are distributed among this set of layers where nodes in each layers follow a listen/sleep schedule that is skewed in time compared to the schedules of the other layers. Therefore, the listen periods of the nodes in different layers are non-overlapping. A node in ML-MAC algorithm wakes up only at its allocated layer. Therefore, ML-MAC requires a lesser amount of energy than S-MAC because the listen period of a node in ML-MAC is shorter than the listen period of the frame in S-MAC. So there are three main advantages than S-MAC of adopting multiples layers in ML-MAC: Reduced energy consumption, Low average, Extended network lifetime. Figure 3 shows how each frame is sub-divided into layers.

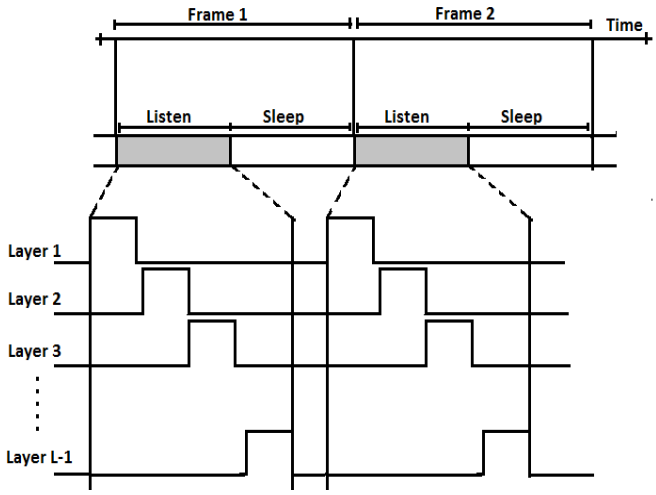

Fig. 2: Design overview of ML-MAC

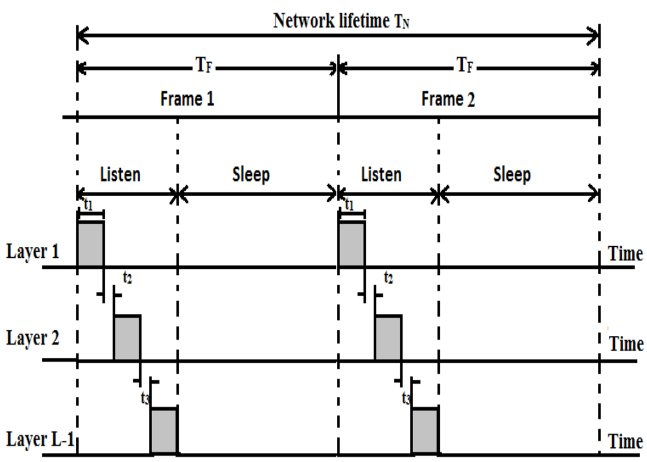

Fig. 3: Network lifetime T_N is split into N_F frames and Timing parameters of ML-MAC

III. Design of Energy-Aware Slotted ML-MAC Algorithm for Wireless Sensor Network

Slotted ML-MAC algorithm is a procedure to reduce node power consumption which is already attained by ML-MAC. Like ML-MAC, Slotted ML-MAC is also a distributed contention-based MAC algorithm and also self-organizing MAC algorithm as it does not require a central node to control the operation of the nodes. The time in Slotted ML-MAC is divided into frames and each frame is divided into two schedule: listen and sleep which is shown in Figure 4. The listen schedule is subdivided into L non overlapping layers and again each layer is divided into two slotted part which is shown in Figure 5. Nodes are distributed among the slotted part of each layer where nodes in each slotted part of each layer follow the listen/sleep schedule that is skewed in time compared to the schedules of the other slotted part of the layers. Therefore, the listen schedules of the nodes in different slotted part of layers are non-overlapping and a node in Slotted ML-MAC algorithm wakes up only at its allocated slotted part of the layer. So Slotted ML-MAC consumes less amount of energy than ML-MAC as the listen schedule of a node in Slotted ML-MAC is shorter than the listen schedule of a node in ML-MAC. Therefore, three main advantages are there in Slotted ML-MAC than ML-MAC, i.e., reduced energy consumption, low average traffic, extended network lifetime. The design parameters that need to be analyzed to study the achievement of Slotted ML-MAC are;

T_R: Maximum response time | T_N: Network lifetime
τ_ρ : Propagation delay | T_F: Frame duration
τ_t : Packet transmission delay | τ_d : Clock drift delay
N_F: Number of fames | A : Slot duration
t_1 : Layer duration | S : Number of slot
t_2:Guard time between layers | g_1:Guard time between slots
λ: Average packet rate per node | L:Number of access layers
ρ:Average node power consumption
n:Total number of nodes in the network

Steps for the design of Slotted ML-MAC : To design Slotted ML-MAC, the value of five parameters are important. i.e., frame duration T_F , slot duration A, number of slot S, listening period per layer t_1, number of layer L. The following design procedure is described below for a given application with its design specifications and requirement [12].

Step-1 : Calculating the frame duration T_F

For a given maximum response time delay T_R that is governed by the time to respond and to report events, the frames duration T_F is bounded as:

$$T_F > T_R \tag{1}$$

For all layers, T_F is bounded by total listening time :

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

Where t_1 is the listening period per layer which is evaluated in step 3 :

$$\frac{T_N}{T_R} \leq N_F < \frac{T_N}{t_1} \tag{3}$$

Step-2 : Calculating the slot duration per layer A and estimating the number of slot S

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

$$t_1 > A \times S \tag{4}$$

From equation (3) and equation (4), it is bounded as:

$$A \leq \frac{T_N}{N_F \times S} \tag{5}$$

The listening time of each layer should follow by:

$$S(A + g_1) \leq t_1 \tag{6}$$

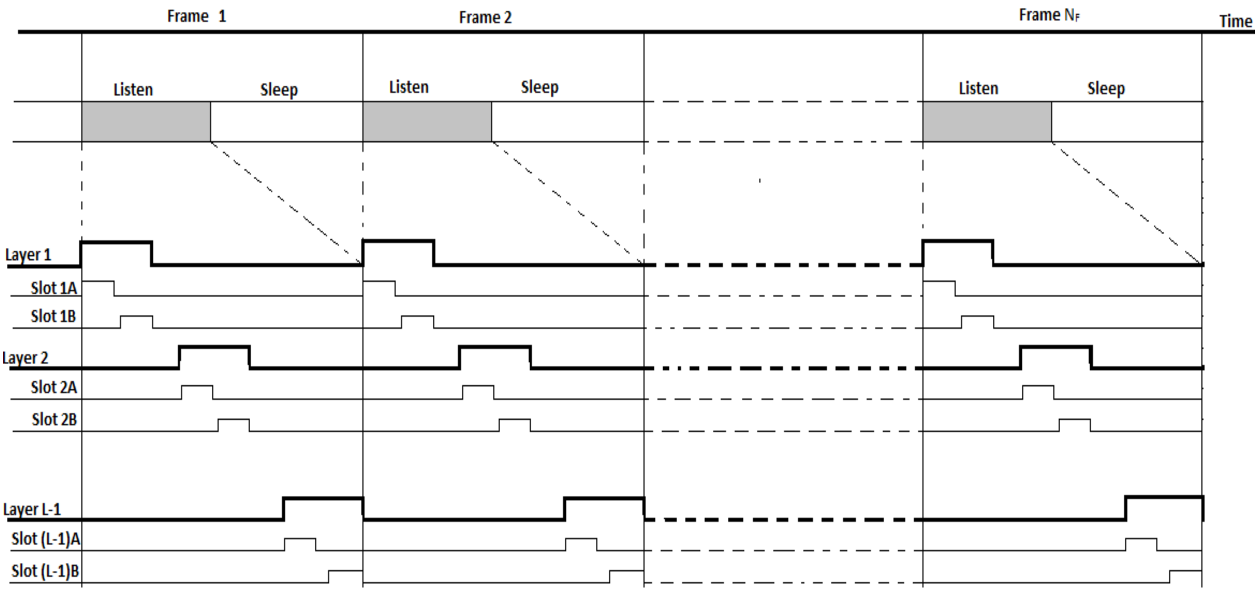

Fig. 4: Design overview of Slotted ML-MAC

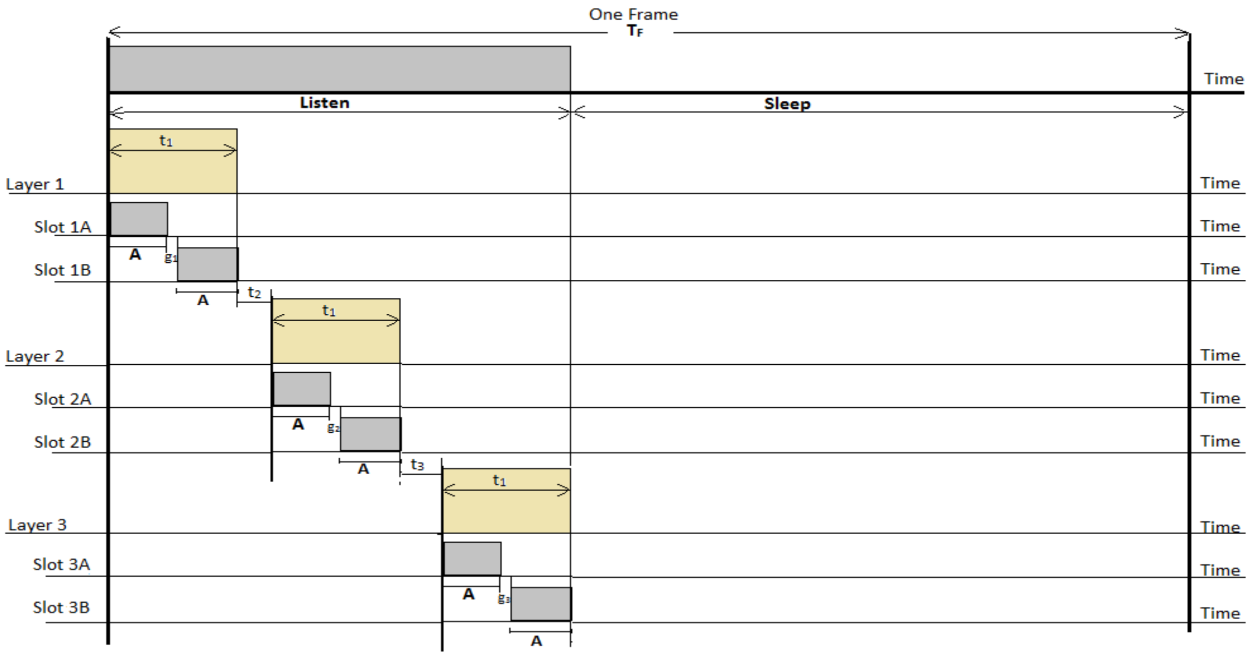

Fig. 5: Timing parameters of one frame for Slotted ML-MAC

Where g_1 is the guard time between the slotted part of the layers. Therefore, the number of slot is governed by

$$S \leq \frac{t_1}{A+g_1} \quad (7)$$

Step-3 : Calculating the listening period per layer t_1

The listening period of one layer t_1 is governed by the battery capacity C (mAh : mili ampere hour) and the average node power consumption ρ :

$$\rho \times t_1 \times N_F \leq C \times V \quad (8)$$

Where V is the average output voltage of the battery. From equation (8), t_1 is bounded as :

$$t_1 \leq \frac{C \times V}{\rho \times N_F} \quad (9)$$

$$A \times S \leq \frac{C \times V}{\rho \times N_F} \quad (10)$$

Also t_1 is bounded by the time needed to send at least one packet which is given by following equation :

$$t_1 > \tau_t + \tau_p + 2\tau_d + W\tau_p \quad (11)$$

Thus from equation (10) and (11), t_1 is bounded as :

$$\tau_t + \tau_p + 2\tau_d + W\tau_p < t_1 \leq \frac{C \times V}{\rho \times N_F} \quad (12)$$

Step-4 : Estimating the number of layers L

The average traffic generated per frame determine how many number of layers should be used which is given by the below equation :

$$\lambda_{avg} = n \times \lambda \times T_F \qquad (13)$$

So, the total listen time should be greater than the time needed to send the entire packet generated by the nodes :

$$L \times S \times A > \lambda_{avg} \times \left(\tau_t + \tau_p + 2\tau_d + \frac{W}{2}\tau_p\right) \qquad (14)$$

L is bounded as given below from equation (14)

$$L \geq \frac{\lambda_{avg} \times (\tau_t + \tau_p + 2\tau_d + (W/2)\tau_p)}{S \times A} \qquad (15)$$

However, the guard time between layers t_2 is governed by the inequality :

$$t_2 > \tau_p + 2\tau_d \qquad (16)$$

Therefore, the upper limit in L is given in below :

$$L(t_1 + t_2) \leq T_F \qquad (17)$$

Using equation (15) - (17), L should follow the below design bounds :

$$\frac{\lambda_{avg} \times (\tau_t + \tau_p + 2\tau_d + (W/2)\tau_p)}{S \times A} \leq L \leq \frac{T_F}{t_1 + t_2} \qquad (18)$$

The delay limitations and buffer size in the node can be used to determine the values of these timing parameters and to specify how many layers should be deployed to get the best behavior.

IV. Algorithm for Slotted ML-MAC

The followings are the procedure of Slotted ML-MAC algorithm.

- The layers of each frame is divided into two slotted part. The nodes are distributed into different slotted parts of each layer in frames using Uniform distributed function.
- Then traffic for each node in slotted part of layers is generated according to a shifted Poisson's distribution function.
- Schedule is defined and it is dynamically changed according to the traffic in each slotted part of layer of the frame conditions. In a scheduling, schedule of a node was changed according to which node it wants to communicate with means which one will be the destination node.
- If the sender and receiver nodes are in the different slots of the same layer then no change has been made to scheduling otherwise the sender has to locate in slotted part of the layer of the receiver. Hence has to wake in two slotted part of layers in same active period.
- First find out which slotted part of the layer of the frame has the least amount of traffic on it. Then it changed the schedule of the receiver and sender node such that they will both wake in the slot of the frame with least traffic.
- Traffic was calculated using distribute (nodes, slot, layers, frames) matrix nodes that want to transmit packets in the slotted part of the layers. All the nodes follow this. So sender does not have to wake twice in the same period and also less collision will be occurred.

The behavior of Slotted ML-MAC is compared with ML-MAC and S-MAC using MATLAB. The assumptions for the simulation of ML-MAC are:

- A sensor node generates packets that follow Poisson distribution.
- Time is split into frames where each frame is composed of listen and sleep periods.
- Each listen time of a frame is divided into L numbers of layers and each layer is sub-divided into two slot.
- Each node has three routines, i.e., transmit, sleep and listen. Nodes have limited transmit and receive buffer sizes. So the packets will not be dropped as they are all ultimately going to be sent to their destinations.
- All MAC operations are based on the IEEE 802.11 and the wireless channel is assumed to be perfect, i.e., there is no bandwidth constraint.
- The radio transceiver of the node is TR 1000 from RF monolithic [13].

Slotted ML-MAC process flow is shown in Figure 6.

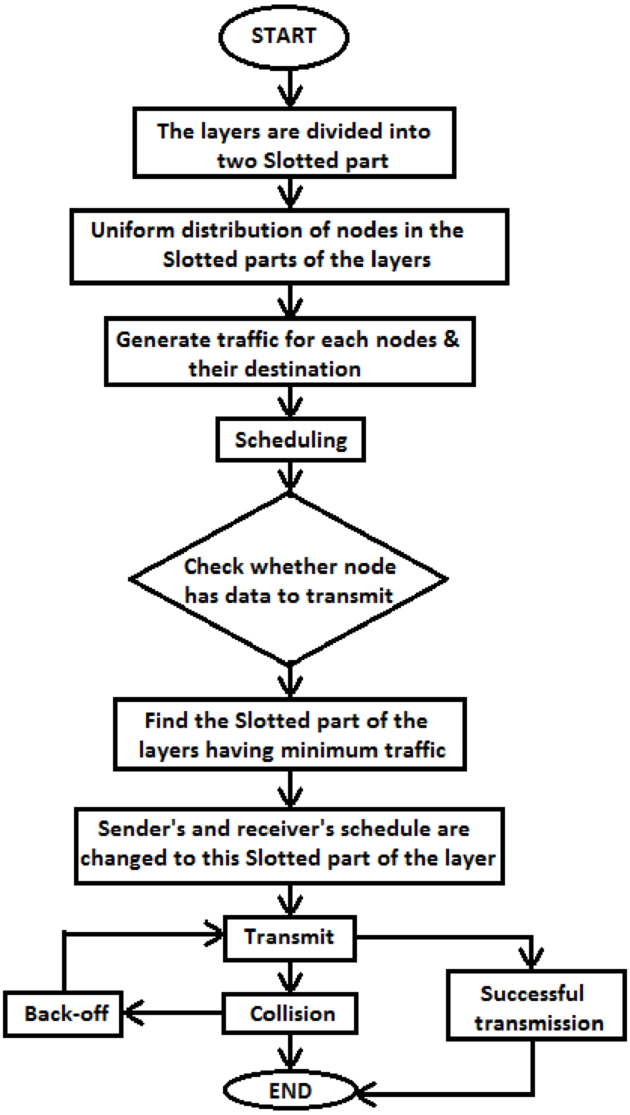

Fig. 6: Slotted ML-MAC process flow

The parameters, assumed for the simulation, are given in Table 1.

Table 1

Parameter	Value
Average message inter-arrival time, T	2-10s
Number of layers, L	1-10
Number of slot, S	2
Number of nodes, n	100
Frame duration, T_F	1 s
Layer duration, t_l	0.3/L s
Node sleeping power	15 µW
Node listening power	13.5 mW
Node transmitting power	24.75 mW
Number of initial reservation slots, W	8
Node transmission data rate	19.2 kbps
Average packet length, α	38 Bytes
Simulation time	200 s

V.TRAFFIC INTER-ARRIVAL TIME MODEL

Poisson distribution used for the generation of traffic is described in the traffic inter-arrival model in Figure 7. It states that nodes statistically generate traffic that is based on an exponentially distributed inter-arrival time. To test the algorithm's behaviour for different arrival rates assume that the inter-arrival time between two successive packets be the random variable T, the probability density function (PDF) for the inter-arrival time of Poisson traffic follows the exponential distribution that can be written as [12]:

$$f_T(t) = \lambda e^{-\lambda t} \quad (19)$$

Where, λ is the average data rate, σ is maximum burst rate and α is the average packet length in bits. The inter-arrival time distribution is modified to get the shifted exponential distribution can be described as:

$$\lambda_T(t) = b e^{-b(t-a)} \text{ for } t \geq a \quad (20)$$

Where, a: Position parameter which represents the minimum time between adjacent packets, a > 0 and b: The shape parameter that describe how fast the exponential function decays with time. The values of a and b for a source with parameters λ, σ and α can be evaluated as:

$$a = \frac{\alpha}{\sigma} \quad (21)$$

$$b = \frac{1}{\alpha} \times \frac{\sigma\lambda}{\sigma-\lambda} \quad (22)$$

$$\lambda = \frac{1}{T} \quad (23)$$

$$\sigma = \frac{1}{T-\Theta} \quad (24)$$

Θ is a constant value between 1 and T-1, but for simulation it has taken 1. The average inter-arrival time T of the packets in this simulation was taken from 2-10 s and the average packet length α was assumed to be fixed with only 38 bytes as most of the wireless networks have a small packet size.

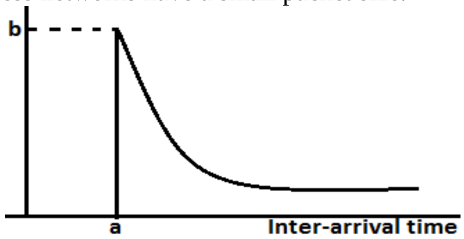

Fig. 7: Biased exponential distributed with the two design parameters 'a' and 'b'

VI. SIMULATION AND RESULTS

The traffic is first generated for all the nodes in the networks for the entire simulation time i.e., 200 s. Each packets generated from any node is stored in the transmit buffer and is allocated at arrival time, destination node address and reservation slot address. These are required to calculate the time and the energy required to send that packet to its destination. The listen period is 300 ms for Slotted ML-MAC with L layers and two slotted part (S=2). The size of a data packet takes only 20ms to send in a typical radio channel. The traffic is analyzed by the time index and checking for packets until the end of simulation. Here, the time index is set to be frame duration/1000, i.e., frames are split into 1000 slots. The total energy consumed by each node over the entire simulation time is determined by evaluating the time of each node spends in the three routines, i.e., listen, transmit, sleep.

$$E_{total} = (T_{listen} \times P_{listen}) + (T_{transmit} \times P_{transmit}) + (T_{sleep} \times P_{sleep}) \quad (25)$$

Then the total energy consumed by the node is calculated by multiplying the total time nodes spend in each routine with the amount of power consumed in that routine.

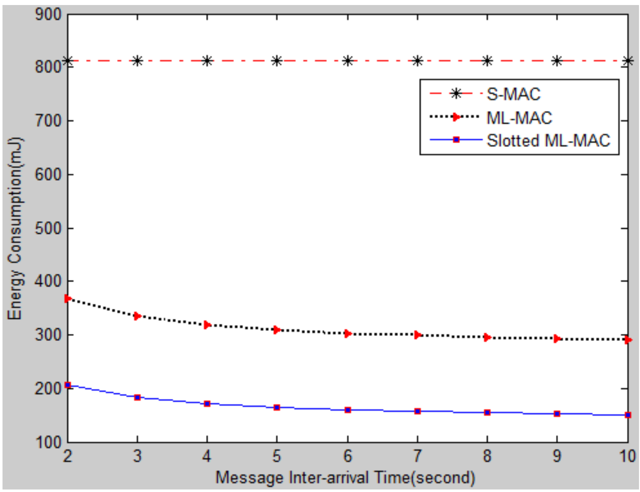

Fig. 8: Total energy consumption per node for S-MAC, ML-MAC and Slotted ML-MAC (L=3,S=2); for non-coherent traffic

Figure 8 show the total energy consumption by a node for S-MAC, ML-MAC and Slotted ML-MAC where L=3, S=2; for non-coherent case. If a node can transmit packets to any other nodes in different slotted parts of the same access layer and also the different slotted parts of other layers, then this case is called the non-coherent case. When the traffic is heavy, i.e., the message inter-arrival time is less than about 5s, ML-MAC consumes 55% less energy than S-MAC and Slotted ML-MAC consumes 27% less energy than ML-MAC and 75% less than S-MAC. When the traffic is light, i.e., the message inter-arrival time is greater than about 5s, ML-MAC consumes 65% less energy than S-MAC and Slotted ML-MAC consumes 48% less energy than ML-MAC and 81% less than S-MAC.

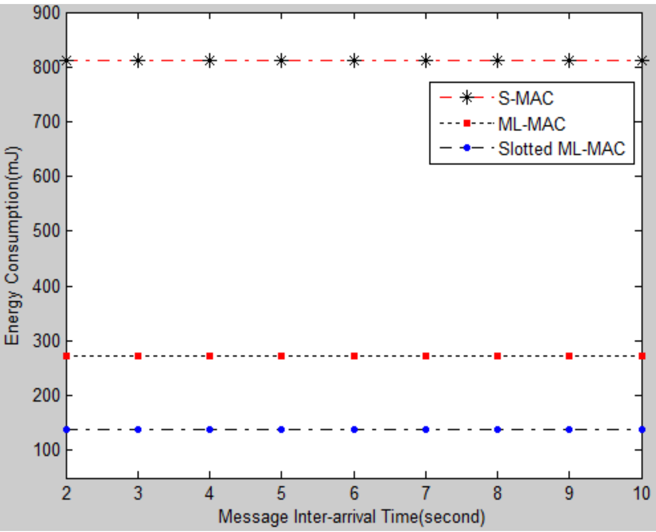

Fig. 9: Total energy consumption per node for S-MAC, ML-MAC and Slotted ML-MAC (L=3,S=2); for coherent traffic

Figure 9 shows the total energy consumption per node for S-MAC, ML-MAC and Slotted ML-MAC where L=3, S=2; for coherent case. If all traffic starting form a node is destined to other nodes in the slotted parts of the same access layer, then this case is the coherent case. Here ML-MAC consumes 67% less energy than S-MAC and Slotted ML-MAC consumes 49% less energy than ML-MAC and 83% less than S-MAC.

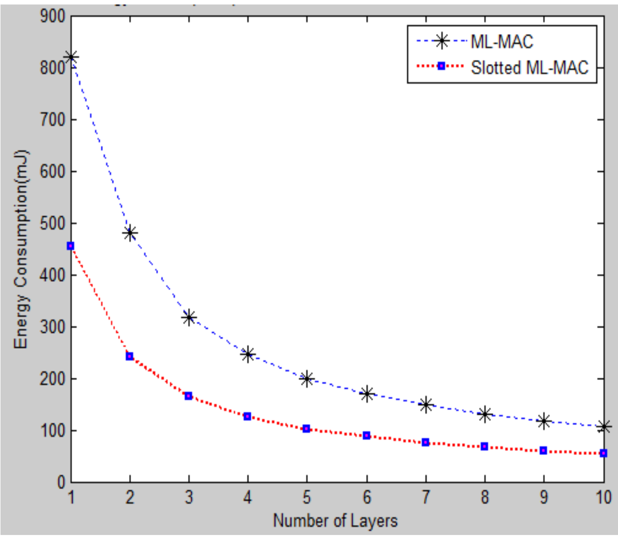

Fig. 10: Total energy consumption per node for ML-MAC and Slotted ML-MAC (L=3,S=2); for non-coherent case

Figure 10 shows the average energy consumption per node verses for ML-MAC and Slotted ML-MAC (L=3, S=2) in the non-coherent case where message inter-arrival time=5s and λ=0.2packets/s. The energy consumption decreases rapidly up to L=5 and after five layers the nodes spend more time waking up at different schedules, so energy saving is not sufficient. When the traffic is light, i.e., the message inter-arrival time is less than about 5s, then Slotted ML-MAC consumes 45% less energy than ML-MAC and when the traffic is heavy, i.e., the message inter-arrival time is greater than about 5s, then Slotted ML-MAC consumes 49% less energy than ML-MAC.

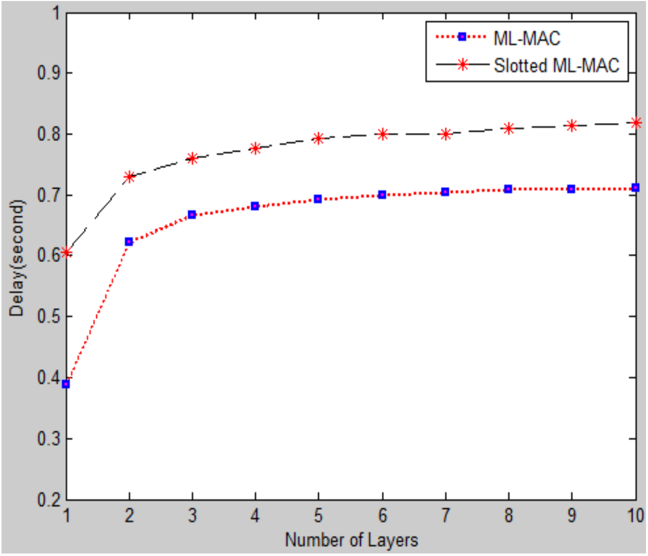

Fig. 11: Average delay for all packets sent for ML-MAC and Slotted ML-MAC (L=3,S=2); for non-coherent case

The average delay for all packets for ML-MAC and Slotted ML-MAC (L=3, S=2) in non-coherent case where the message inter-arrival time=5s and λ=0.2packets/s are shown in Figure 11. As the nodes sleep more in Slotted ML-MAC than ML-MAC, packets are encounter more delay. The latency is the delay time that a packet may encounter because it is stored in the transmit buffer of a node until the packet is sent successfully to its destination without collision. Here, the delay is composed of two components, i.e., Queuing delay and Transmission delay. In both algorithm the delay increase rapidly if the number of the layer is less than three and when more layers are added, then packets are not encounter more delays as the packets are buffered for next frame cycle. Here Slotted ML-MAC consumes about 34% more delay than ML-MAC.

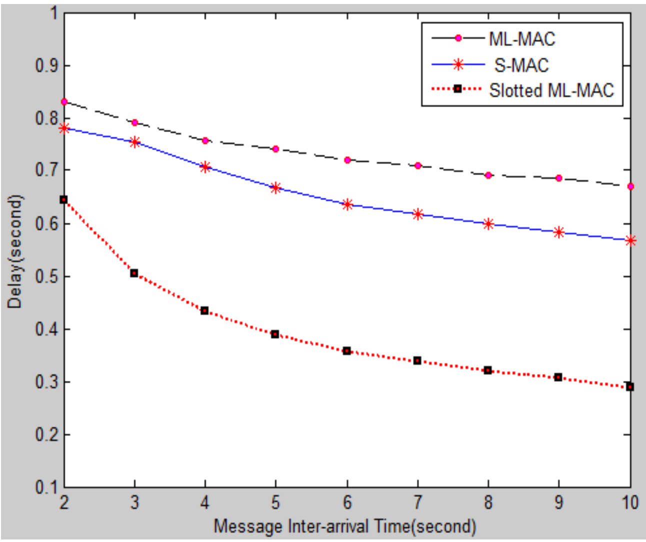

Fig. 12: Average delays for all packets sent for S-MAC, ML-MAC and Slotted ML-MAC (L=3,S=2); for non-coherent case

The average delay for all packets for three algorithms: S-MAC, ML-MAC and Slotted ML-MAC (L=3, S=2) in non-coherent case are shown in Figure 12. This results Slotted ML-MAC in non-coherent traffic has longer delay than ML-MAC and ML-MAC in non-coherent traffic has longer delay than S-MAC, i.e., If the message inter-arrival time < 5s, then ML-MAC consumes 15% more delay than S-MAC and Slotted ML-MAC consumes 1% more delay than ML-MAC and 22% more delay than S-MAC. If the message inter-arrival time > 5s, then ML-MAC consume 50% more delay than S-MAC and Slotted ML-MAC consumes 15% more delay than ML-MAC and 57% more delay than S-MAC.

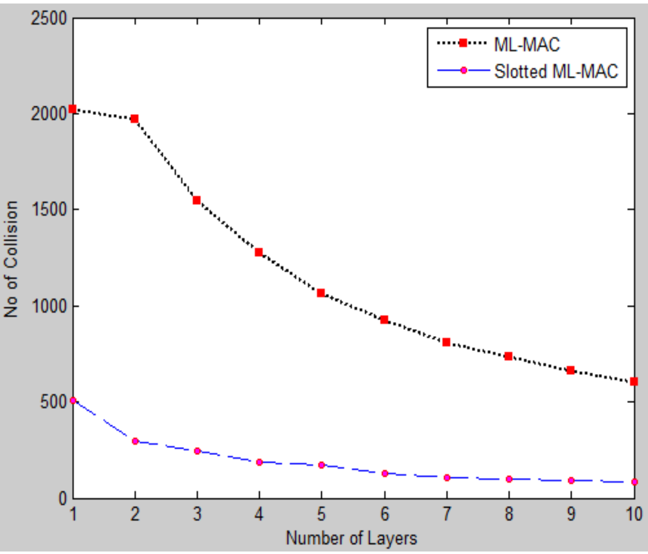

Fig. 13: Number of collisions for ML-MAC and Slotted ML-MAC (L=3,S=2); for the non-coherent traffic

Figure 13 results the number of collision for ML-MAC and Slotted ML-MAC algorithm keeping the message inter-arrival time constant at 5s, i.e., λ=0.2packets/s and σ=0.25packets/s in non-coherent traffic. The number of collision decreases dramatically by adding more layers. Here it shown that when the message inter-arrival time < 5s, the number of collisions for Slotted ML-MAC is 75% less than ML-MAC, when the message inter-arrival time > 5s, the number of collisions for Slotted ML-MAC is 85% less than ML-MAC.

VII. Conclusion

Slotted ML-MAC algorithm is proposed in this paper which is an energy-efficient MAC algorithm in WSNs. In this algorithm, nodes are distributed in the slotted parts of each layer in order to minimize the idle listening time. The simulation and results shows the energy consumption of Slotted ML-MAC comparing with S-MAC and ML-MAC. The listening periods of a node in different slotted part of layers are non-overlapping. So It minimize energy consumption from two sources of energy inefficiency: idle listening and collision. With the specified parameters assumption, the results of Slotted ML-MAC algorithm are showing the Slotted ML-MAC outperforms S-MAC and ML-MAC in conserving energy by having an extremely low duty cycle and minimizing the probability of collisions.

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