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An Energy-Efficient Slotted MAC (SL-MAC) Protocol for Wireless Sensor Networks

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Abstract*— The efficient use of energy is an important performance target to magnify the lifetime of wireless sensor networks (WSNs). The idle listening of sensor nodes is one of the primary causes of energy waste; so many typical MAC protocols are designed to rescue power by placing the radio in the low-power sleep mode. In this paper, a new energy-efficient Slotted MAC (SL-MAC) protocol is proposed for wireless sensor networks. It is designed with three main features: 1) reducing energy consumption 2) minimizing the number of collisions 3) reducing average packet delay. Sensor nodes in SL-MAC have a very short listen time period which would reduce the energy required to communicate with other nodes. Also, the number of collisions is minimized by using Back-off algorithm in SL-MAC. This saves the energy required to re-send the corrupted packets. Simulation results show much better performance of the energy consumption compared with the existing MAC Protocols.

***Index Terms* — Energy management, medium access control (MAC), wireless sensor networks (WSN).**

I. INTRODUCTION

A wireless sensor network is a collection of a large number of sensor nodes that are deployed in an ad-hoc manner and communicate using a short-range radio channel. Most sensor nodes are battery operated and normally they cannot be recharged due to its deployment in harsh and remote environment. Therefore, energy efficiency is a very critical issue to prolong the networks lifetime [1, 2, 3]. In this paper, we lay stress on the contention based protocols, which use an active/sleep mode frame to save energy consumption.

There are four major sources of energy waste [1]: collision, overhearing, control packet overhead and idle listening. In IEEE 802.11, In the active/sleep cycle schemes, sensor nodes periodically turn off their radio and go into sleep mode, which will reduce the idle listening excellently. The frame length T_{frame} comprises of the listen and the sleep time. We define the duty cycle as T_{listen} / T_{frame} , T_{listen} is the active (listen) time of a cycle.

In this paper, a new MAC protocol scheme, called Slotted MAC protocol (SL-MAC) is proposed. In the proposed technique it is attempted to reduce node power consumption by reducing the number of collisions.SL-MAC is a distributed contention based MAC protocol where nodes discover their neighbours based on their radio signal level. Also, SL-MAC is a self-organizing MAC protocol that does not require a central node to control the operation of the nodes.

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This paper is structured as follows. Related work is introduced in section II; the energy consumption analysis is in section III; Section IV gives explanation of the new scheme design, and Section V is describes the simulation and results.

II. RELATED WORKS

A good wireless MAC protocol must possess the following primary attributes [2]: *energy efficiency, scalability and adaptability to changes*. Attributes such as *latency, throughput, and bandwidth utilization* are not of primary concern. Based on the wireless local networks IEEE 802.11 distributed coordination function (DCF) MAC protocol, researchers have proposed many [1-6] MAC schemes for WSN.

MAC protocols can be classified into two types depending on the way the access is being controlled: reservation-based and contention-based [10]. Each of these access methods has its own advantages and disadvantages. In reservation-based MAC protocols, the channel is reserved for the nodes for a certain amount of time. Reservation-based MAC protocols have many disadvantages [5, 6] that make them difficult to implement for wireless sensor networks. However, reservation-based MAC protocols are collision-free since each node is assigned a specific slot that is reserved specifically for a node to use for communication leading to very low duty cycle [7, 8]. Also, when nodes turn off their radio port during reservation slots for others, they are not affected by others' traffic. Therefore, reservation-based MAC protocols reduce the energy consumption from most of the major sources of energy waste, ***i.e.,*** idle listening, collision, and overhearing. TRAMA [9] (Traffic-adaptive medium access protocol) is a reservation-based MAC protocol that reduces energy consumption by being collision free and by making the nodes switch to sleep mode when they are idle. The schedules in TRAMA are dynamic and adaptive based on current traffic patterns.

On the other hand, nodes in contention-based MAC protocols determine if they can access the medium by sensing the shared channel and competing to get access to it instead of defining schedules for access. Contention-based MAC protocols have some drawbacks in the attributes related to the sources of energy consumption, as contention based protocols consume more power than reservation-based protocols. Therefore, many researchers are trying to define contention-based MAC protocols that overcome these sources of energy inefficiency. The IEEE 802.11 [4] is an international standard of physical and MAC layer specifications for wireless networks. It uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). S-MAC [1, 2] is a contention-based approach that modified the IEEE 802.11 standard to be suitable for sensor networks.

As shown in Fig. 1, S-MAC divides time into number of frames and each frame is divided into active period and sleep period. The ratio of the active period to the frame length is called the duty cycle. Communication occurs only in the active period. Packets that are generated by nodes during the sleep period of the frame are buffered for the next frame cycle. This increases the latency because the sender nodes has to wait for the active period of next frame.

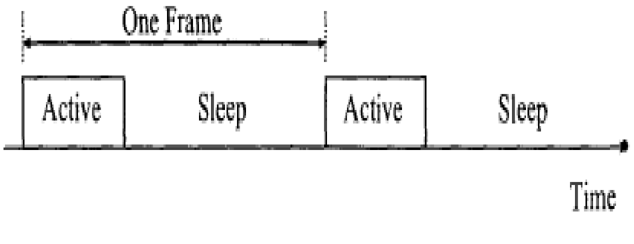

Fig. 1 The periodic listen and sleep mode in S-MAC protocol

Synchronization in S-MAC is not critical because clock drift is typically much smaller than the active period. S-MAC eliminates clustering to reduce inter-cluster communication and interference, but at the expense of making the listening period longer. When a new node in S-MAC joins the network, it first waits for a certain amount of time to get a schedule from another node and then follows that schedule. If it does not hear any schedule, it chooses its own and broadcasts it to the other nodes. After that, all nodes broadcast their schedules periodically using the control packets SYNC which have the time of the next frame cycle. Using this scheme a node can easily join the network. The duty cycle in S-MAC is fixed and predefined depending on the application requirements, such as latency and buffer limitation. Therefore, many nodes might be idle during their listen periods which can lead to a large wastage of energy. Consequently, this is not an optimal solution to minimize the idle listening time because traffic in sensor networks varies.

III. SL-MAC PROTOCOL DESIGN

Sensor nodes in proposed SL-MAC have a very short listening time because each listen period of frames are divided into fixed no. of slots, which would reduce the energy, required communicating with other nodes. Also, the number of collisions in cases where two or more nodes try to send at the same time is minimized in SL-MAC. This saves the energy required to resend the corrupted packets. Simulation results may show much better performance of the energy consumption compared with the existing MAC Protocols. There are three main advantages of adopting multiple slots in SL-MAC:

1. Reduced energy consumption. The listen period for the nodes in each phase is reduced in proportion to the number of slots employed. Therefore, energy loss during listen periods in SL-MAC is reduced compared to S-MAC protocol.

2. Low average traffic. The number of nodes associated with a slot in SL-MAC is a fraction of the total nodes in the network. This results in less average traffic and a reduced chance of collisions. Therefore, the probability of collision in SL-MAC is reduced, which saves the energy required for retransmitting the collided packets and also the associated control packets.

3. Extended network lifetime. By reducing the energy consumption in the nodes, the lifetime of the nodes and the network are increased.

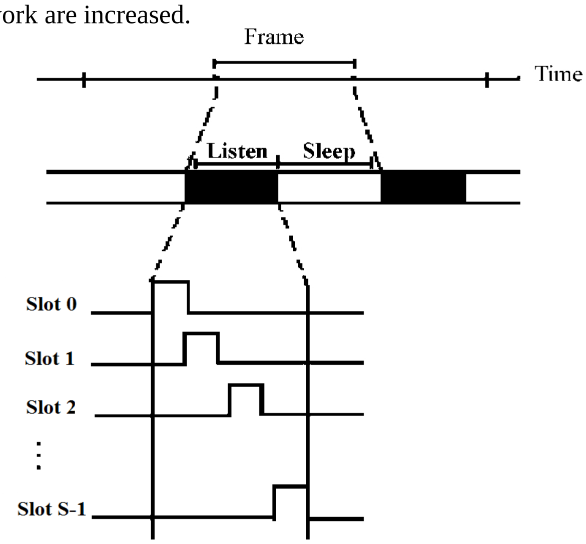

Fig. 2 Design overview of SL-MAC

As Fig. 2 shows, time in SL-MAC is divided into frames and each frame is divided into two periods: listen and sleep. The active period is sub-divided into S non-overlapping slots. Nodes are distributed among this set of slots dynamically based on traffic condition where nodes in each slot follow a listen/sleep schedule that is skewed in time compared to the schedules of the other slots. Therefore, the listen periods of the nodes in different slots are non-overlapping. A node in SL-MAC protocol wakes up only its assigned slots. I.e. The type of traffic in SL-MAC can affect the performance of the protocol. If all the traffic emanating from a node is destined to other nodes in the same slot, ***i.e.,*** the source and destination are in the same access slot, and then nodes do not have to wake up at different slots. This case is called the coherent traffic. However, if a node can send to any other nodes in a different access slot, which is called non-coherent traffic, then nodes might wake up at different slots if they have packets destined to nodes in other slots.

Therefore, SL-MAC requires a lesser amount of energy than S-MAC because the listen period of a node in SL-MAC is shorter than the listen period of the frame in S-MAC and by changing schedule of both transmitter & receiver node depending upon traffic in each slot of a frame. i.e., whenever a node has to transmit to another node even if they are in same slot or in different slots. Both transmitter & receiver will wake up in the node with the least traffic for transmission of packets.

Steps involved in the design of SL-MAC Protocol:

1. The nodes are distributed into different slots using Uniform distributed function.
2. Then traffic for each node in slots is generated according to a shifted Poisson's distribution function.
3. The schedule is defined.

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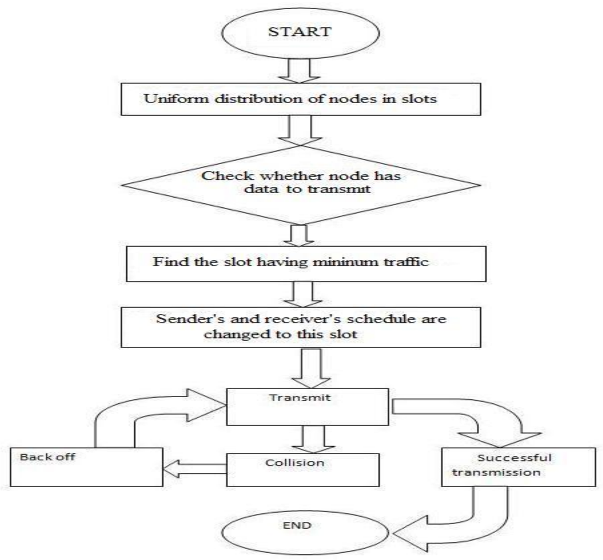
4. Schedule is dynamically changed according to 'the traffic in each slot of the frame' conditions. In a state scheduling, schedule of a node was changed according to which node it wants to communicate with.
5. If the sender and receiver nodes are in the same slot then no change has been made to scheduling otherwise the transmitter (sender) has to locate in the slot of the receiver. Hence has to wake in two slots in the same active period.
6. In our Model first we found out which slot of the frame has the least amount of traffic on it. Then we changed the schedule of the receiver and transmitter node such that they will both wake in the slot of the frame with least traffic.
7. Traffic was calculated using a state (nodes, slots, frames) matrix nodes that want to transmit has state=2 and those in slot will have state=1.
8. This is done for all the nodes. Hence transmitter does not have to wake twice in the same period also less collision will be there.

IV. SL-MAC: PROCESS FLOW



A. Design parameters:

This subsection discusses the design parameters that need to be analysed to study the performance of SL-MAC.

A network application has the following design specifications as shown in Figure 3**:**

N **:** Total number of nodes in the network.
λ **:** Average packet rate per node.
T_{net} **:** Network lifetime.
T_{res} **:** Maximum response time delay.
τ_{trans} **:** Packet transmission delay.
τ_{prop} **:** Propagation delay.
τ_{delay} **:** Clock drift delay.
C **:** Battery capacity.
ρ **:** Average node power consumption.

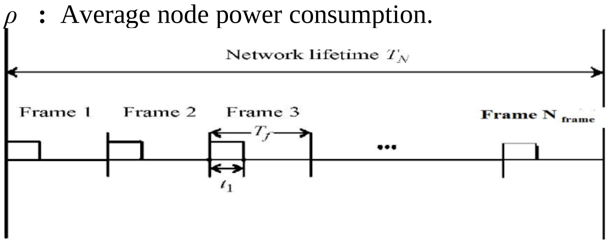


Fig. 3 Network lifetime T_N is divided into N_{frame} frames

In addition, as shown in Fig. 4, the design parameters of SL-MAC include the following:

S**:** Number of access slots
.T_{frame}**:** Frame duration.
N_{frame}**:** Number of frames.
t_1**:** slot duration.
t_2 **:** Dead time between slots.

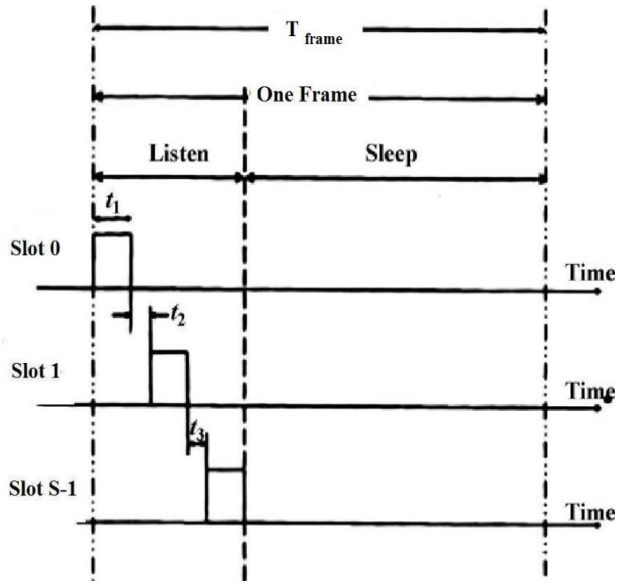


Fig. 4 Timing parameters of SL-MAC**:** slot duration t_1 , dead time between successive slots t_2, and frame duration T_{frame}.

B. Design Procedure:

The values of the design parameters of SL-MAC listed above can be obtained by the following design procedure described below :

Step 1 (Calculating the frame duration T_{frame} *) :*

For a given maximum response time delay T_{res} that is governed by the time to respond and to report events, the frame duration T_{frame} is bounded from above by:

$$T_{frame} \le T_{res} \quad (1)$$

T_{frame} is also bounded by total listening time for all the slots:

$$T_{frame} > t_1 \times S \quad (2)$$

where t_1 is the listening period for one slot that will be found from step 2 and S is the number of slots.

The number of frames N_{frame} is bounded by:

$$\frac{T_{net}}{T_{res}} \le N_{frame} < \frac{T_{net}}{t_1 \times S} \quad (3)$$

Step 2 (Calculating the listening period per slot t_1*):*

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The duration of the listening period for one slot t_1 is governed by the battery capacity C (mAh – milli ampere hour) and the average node power consumption ρ **:**

$$\rho \times t_1 \times N_{frame} \le C \times v \quad (4)$$

where v is the average output voltage of the battery.

Thus from (4), t_1 is bounded as:

$$t_1 \le \frac{C \times v}{\rho \times N_{frame}} \quad (5)$$

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

$$t_1 > \tau_{trans} + \tau_{prop} + 2\tau_{delay} + W\tau_{prop} \quad (6)$$

where τ_{trans} is the packet transmission delay, τ_{prop} is the propagation delay, τ_{delay} is the clock drift delay, and W is the maximum number of reservation slots which is called the window size.

Thus from (5) and (6), t_1 is bounded by**:**

$$t_1 + \tau_{prop} + 2\tau_{delay} + W\tau_{prop} < t_1 \le \frac{C \times v}{\rho \times N_{frame}} \quad (7)$$

Step 3 (Estimating the number of slots S):

The number of slots S is based on the average traffic generated per frame in each slot which is given by the following equation:

$$\lambda_{avg} = N \times \lambda \times T_{frame} \quad (8)$$

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

$$S \times t_1 > \lambda_{avg} \times (\tau_{trans} + \tau_{prop} + 2\tau_{delay} + \frac{W}{2}\tau_{prop}) \quad (9)$$

Thus from (9), S is bounded as**:**

$$S \ge \frac{\lambda_{avg} \times (\tau_{trans} + \tau_{prop} + 2\tau_{delay} + \frac{W}{2}\tau_{prop})}{t_1} \quad (10)$$

Moreover, the dead time between slots t_2 is governed by the inequality:

$$t_2 > \tau_{prop} + 2\tau_{delay} \quad (11)$$

Therefore, the upper limit in S is:

$$S(t_1 + t_2) \le T_{frame} \quad (12)$$

Thus using (10), (11) and (12), S has the following design bounds:

$$\frac{\lambda_{avg} \times (\tau_{trans} + \tau_{prop} + 2\tau_{delay} + \frac{W}{2}\tau_{prop})}{t_1} \le S \le \frac{T_{frame}}{t_1 + t_2} \quad (13)$$

Other specifications and requirements in the application, such as delay limitations and buffer size in the node, can be used to determine the values of these timing parameters and to specify how many slots should be deployed to get the best performance.

V. SIMULATION AND RESULTS

The performance of SL-MAC is simulated using MATLAB version 7 on a PC machine to compare the results with other MAC protocols that have been proposed for wireless sensor networks. In order to perform the simulations for SL-MAC, the following assumptions are made:

1) A sensor node generates packets that follow Poisson distribution.
2) Time is divided into number of frames where each frame is composed of listen and sleep periods.
3) Each node has three modes of operation: *transmit*, *listen*, and *sleep*.
4) Nodes have unlimited transmit and receive buffer sizes.
5) All MAC operations are based on the IEEE 802.11.
6) The wireless channel is assumed to be perfect, ***i.e.***, there is no bandwidth constraint.

The transmission data rate of this radio transceiver is 19.2 Kbps. According to assumption 4, packets will not be dropped as they are all ultimately going to be sent to their destinations. The parameter values chosen for numerical simulations are summarized in Table 1.

TABLE 1

Parameter	Value	Unit
Average packet inter-arrival time T (range of variation)	1-10	Second
Number of nodes N	50	
Frame duration T_{frame}	1	Second
Listen period T_{listen}	0.3	Second
Number of initial reservation slots W	8	
Node transmitting Power	24.75	mWatt
Node listening Power	13.5	mWatt
Node sleeping power	15	µWatt
Average packet length α	38	Bytes
Simulation time	100	Second

A. *Traffic Inter-arrival time Model:*

The model that describes the generation of traffic in this simulation was chosen to be the Poisson distribution [4]. The assumption of Poisson distribution for the traffic implies that nodes statistically generate traffic that is based on an exponentially distributed inter-arrival time. This traffic model was chosen to test the protocol's performance for different arrival rates. Let the inter-arrival time between two successive packets be the random variable *T*. Then, the *PDF* (Probability Density Function) for the inter-arrival time of Poisson traffic follows the exponential distribution that can be expressed as:

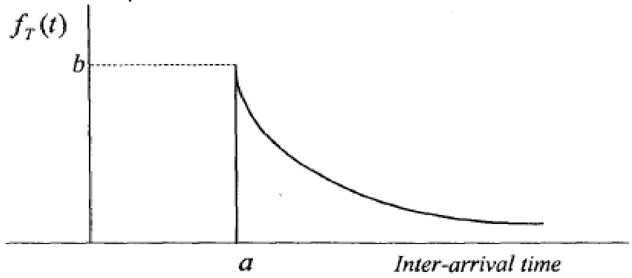

Fig. 5Biased exponential distribution with the two design parameters a and b.

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$$f_T(t) = \lambda e^{-\lambda t} \quad (14)$$

Where, λ is the average packet arrival rate in packets. However, to be more realistic in describing the traffic, the source has to be specified with more parameters than only the average data rate λ. These parameters are:

λ: average data rate.

σ: maximum burst rate.

α: average packet length in bits.

Therefore, the inter-arrival time distribution is modified to get the shifted exponential distribution that can be expressed as:

$$f_T(t) = be^{-b(t-a)} \quad \text{for } T \geq a \quad (15)$$

where $a > 0$ is the position parameter which represents the minimum time between adjacent packets and b is the shape parameter that determines how fast the exponential function decays with time. Fig. 5 shows the biased exponential distribution with the two design parameters a and b.The values of a and b for a source with parameters λ, σ, and α, can be calculated as in from the following equations:

$$a = \frac{\alpha}{\sigma} \quad (16)$$

$$b = \frac{1}{\alpha} \times \frac{\sigma\lambda}{\sigma - \lambda} \quad (17)$$

In this simulation, the average packet length α was assumed to be fixed with only 38 bytes since most wireless sensor networks have a very small packet size. Also, the average inter-arrival time T of the packets in this simulation was varied from 2 to 10 seconds. Therefore, λ and σ can be found based on the packet inter-arrival time from the following two equations:

$$\lambda = \frac{1}{T} \quad (18)$$

$$\sigma = \frac{1}{T - \theta} \quad (19)$$

Where, θ is a constant value between 1 and (T - 1). In this simulation, θ was assumed to be 1.

To make the simulation simpler, the traffic is generated at the beginning of the simulation for all the nodes in the networks for the entire simulation time. Each packet generated from any node is stored in the node transmit buffer and is assigned three flags:

- Arrival time
- Destination node address
- Reservation slot address

These flags are used to calculate the time and the energy required to send that packet to its destination.

B. Traffic destination Model:

The destination of each packet generated by a node is selected using the uniform random distribution for the non-coherent case and coherent case both.

C. Data Gathering

According to Table 1 time is divided into frames of 1s duration and the simulation time is 100s. These values have been specified after running the simulation using different simulation times to ensure all transients have disappeared and enough data has been collected.

The duty cycle is 33% which makes the duration of the listen period 300 ms for the S-MAC and same for SL-MAC with S number of slots. The traffic is analysed by advancing the time index and checking for packets until the end of simulation.

The total energy consumed by each node over the entire simulation time is determined by calculating the time that each node spends in the three modes, ***i e.,*** listen, transmit and sleep. Then, the total time, nodes spend in each mode, is multiplied by the amount of power consumed in that mode to get the total energy consumed by the node.

Delay, in this simulation, is the sum of the time a packet may encounter in the transmit buffer and the time needed to send that packet. Therefore, the queuing delay is the dominant part that affects the delay. Delay is calculated by subtracting the time a packet is delivered to the destination from the time that packet was generated.

The collided nodes have to back-off when collision occurs. The probability of collision is calculated by dividing the number of collisions by the total number of packets generated.

D. Protocol Performance

The main advantage of deploying multiple slots in SL-MAC is the reduction in node energy consumption as the following subsection illustrates. Another advantage of deploying multiple slots in SL-MAC is the reduction in the probability of collisions, which also saves energy that would otherwise have been needed for retransmitting the collided packets.

1. Overall energy consumption

Figure 6 compares the average energy consumed by a node for SL-MAC and S-MAC protocols. Where, we take 3 numbers of slots in each frame in SL-MAC protocol**.** In this simulation coherent and non-coherent both case are used. It shows that SL-MAC consumes lesser energy than S-MAC protocol. In SL-MAC the energy consumption decreases as the number of nodes increases. This has been done because of the fact that now the listen time of nodes is lesser than other MAC protocols. Energy consumption is directly related to the listen period.

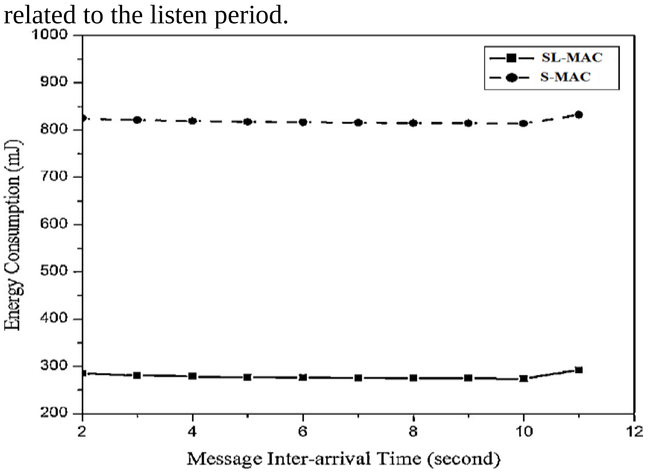

Fig. 6 Total energy consumption per node for SL-MAC and S-MAC with S= 3; for the coherent case

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Fig. 7 compares the average energy consumed by a node for S-MAC and SL-MAC for 3 slots in each frame. Figure 7shows the total energy consumed in a node for the whole simulation time, as the number of slots **S** is increased from 1 to 10 slots using the non-coherent case.

Traffic is generated with an average inter-arrival time T of 10 s (λ = 0.2 Packets/s). Energy consumption by nodes reduces rapidly up to 5slots. However, after five slots, energy saving is not significant as most of the packets are destined to other slots and the nodes spend more time waking up at different schedules. Also, this increases the number of control packets that consumes more energy.

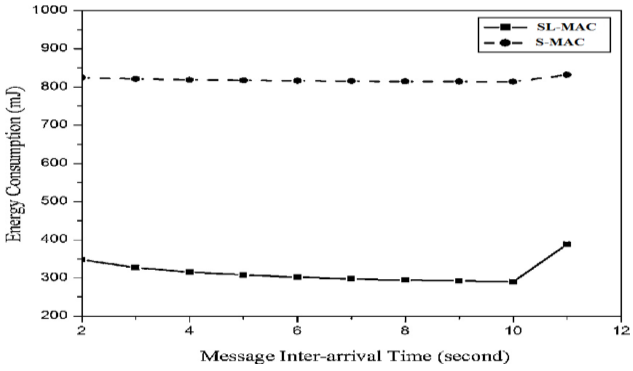

Fig. 7 Energy consumption per node for SL-MAC and S-MAC in the non-coherent case, traffic is fixed: λ = 0.2 packets/s

2. *Average packet delay*

As the nodes are relay more in sleep mode when they have nothing to hear traffic in SL-MAC, packets will encounter more delay. This delay is the latency that a packet may encounter because it is stored in the node transmit buffer until it is transmitted to destination successfully without a collision. Therefore, the delay here is composed of two components:

a. Queuing delay, because a packet could be destined to another slots or it has been generated while the node is in sleep mode.

b. Transmission delay.

This result is shown in Fig. 8 where SL-MAC in the non-coherent case has a longer delay than S-MAC and IEEE802.11 MAC protocols.

Fig. 9 shows the effect of adding more slots on delay for the non-coherent case. As the number of slots increases, packets will not encounter more delay because they are usually buffered for the next or third frame cycle.

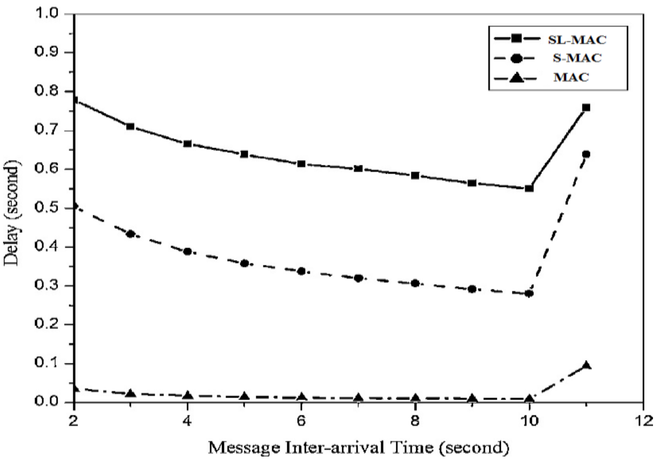

Fig. 8 Average delays for all packets sent for the three protocols: SL MAC,S-MAC and MAC protocols with S= 3; for the non-coherent case.

3. *Number of collisions*

Fig. 10 shows how the number of collisions declines dramatically by adding more slots for SL-MAC using the non-coherent case and fixing the traffic at 0.2 packet per second. The high number of collision in the last result is due to the traffic type generated for the simulation. The values of two traffic parameters λ and σ , are 0.2 and 0.25 packets/s, respectively. Because λ and σ are close to each other, then all 50 nodes generate packets that have around the same arrival times. As a result the number of collision is high.

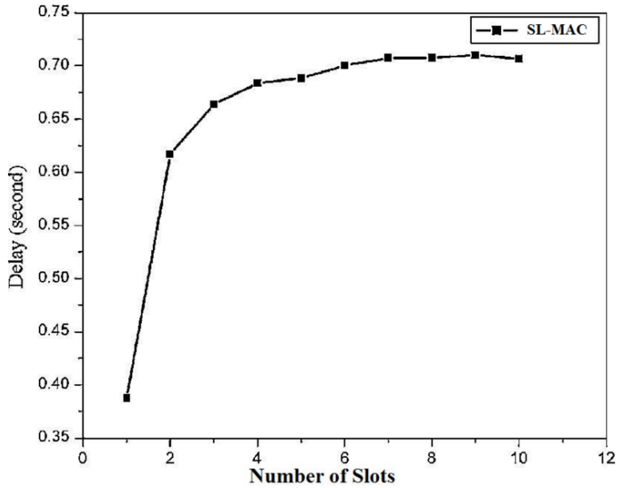

Fig. 9 Average delay for all packets sent for SL-MAC in the non-coherent case, Traffic is fied:λ = 0.2 packets/s

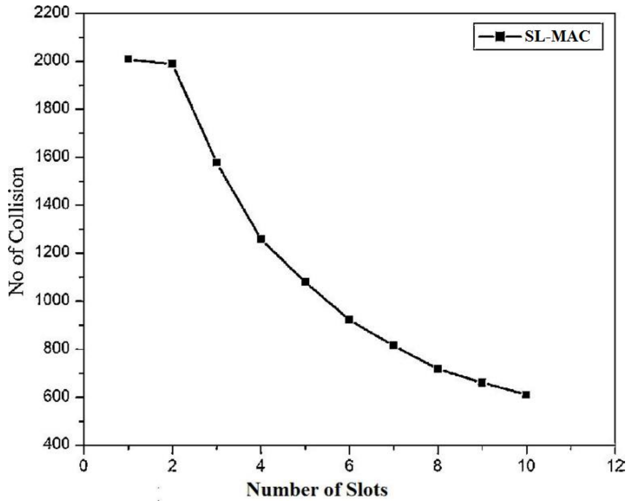

Fig. 10 Number of collisions for SL-MAC in the non-coherent case, traffic is fixed: λ=0.2 packets/s

VI. CONCLUSION

The applications of wireless sensor networks are limitless in the present environment. These can be used in intelligent controllers, as traffic sensor to monitor different routes & find a route with least delay, to sense enemy missile &transport etc in defence applications etc.

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An energy-efficient MAC protocol for wireless sensor networks called SL-MAC is proposed in this work. In SL-MAC with S number of slots, nodes are assigned into S slots dynamically according to traffic condition to reduce the idle listening time by a number proportional to S. The listen period of the nodes in different slots is non-overlapping. This will reduce energy consumption from two sources of energy inefficiency: idle listening and collision. Results showed that SL-MAC outperforms S-MAC in conserving energy by having an extremely low duty cycle, reducing traffic activity at any given time.

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