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An energy-efficient MAC protocol based on node power for wireless sensor networks

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ABSTRACT

Energy consumption is an important issue in Wireless Sensor Networks (WSNs) because wireless sensor nodes are usually battery powered, and an efficient use of the available battery power becomes an important concern especially for those applications where the system is expected to operate for long durations. This necessity for energy efficient operation of a WSN has prompted the development of new protocols in all layers of the communication stack. If the radio transceiver is the most power consuming component of a typical sensor node, large gains can be achieved at the link layer where the Medium Access Control (MAC) protocol controls the usage of the radio transceiver unit. This paper presents an energy-efficient MAC protocol for WSNs. This protocol is designed to achieve low duty cycle, especially for low and medium power nodes and therefore extended network lifetime. Low power nodes in the proposed approach have a very short listening time that would reduce the energy consumption during communication. The simulation results show that the proposed MAC protocol has the best energy saving performance over both the Sensor-MAC (S-MAC) and Multi-Layer MAC (ML-MAC) protocols. The proposed approach saves energy of about 73% more than the S-MAC protocol. It also achieves 23.1 % energy saving compared to ML-MAC protocol in the coherent mode.

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1. Introduction

In recent years, Wireless Sensor Network (WSN) [1] has evolved at a rapid speed, with the advances in sensor technology, low-power electronics, and low-power radio frequency (RF) design. WSN consists of plenty of low-cost sensor nodes which are composed of a single chip with embedded memory, processor, and transceiver. The limited battery capacities of those sensor nodes require energy-efficient operation of the WSN. So the main objective of WSN is minimizing the energy consumption [2], as sensor nodes are assumed to be disposed when they run out of battery power. So more and more work on sensor network has focused on medium access control

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(MAC) protocols since the transceiver consumes a significant amount of energy and the MAC protocol has the most direct control over its utilization [3].

Another possible objective in WSN is minimizing the latency [4]. This objective is especially crucial for time-critical applications such as intrusion detection and tactical systems [5]. However, much MAC protocols aim at energy efficiency and do not provide any real-time guarantee. MAC protocols should be optimized considering both of the energy saving and the latency. The energy consumption and the latency caused idle listening are affected significantly by the Duty Cycle (DC) [6]. Therefore, the MAC protocol scheme in WSN has to be able to establish a communication link for transferring data and saving energy.

Several existing MAC protocols were designed without taking the initial power of each node in the network into consideration. So, this paper offers an energy-efficient MAC protocol based on node power for WSNs. For maximizing the energy efficiency, the suggested solution introduces some more message latency to reduce the energy loss resulting from idle listening. As a result, the proposed MAC protocol can extremely minimize the energy dissipation due to idle listening. This paper is organized as follows. S-MAC [7] and ML-MAC [8-10] protocols are presented in section 2. Section 3 gives the details of the proposed MAC protocol. Section 4 presents the simulation results and a comparison between the proposed MAC, S-MAC, and ML-MAC protocols in coherent mode, it concentrates on issues like threshold power level and layer duration. In section 5, the conclusions are presented.

2. Related Works

The MAC is a sub-layer of the data link layer in OSI model (layer 2) [11]. Recently, varieties of MAC protocols have been proposed for WSNs by researchers. The MAC protocols have to achieve two objectives; formation of the sensor network infrastructure and access fairness. So, MAC protocols have become important in the implementation of WSNs, essentially for the energy consumption and transmission delay.

Energy efficiency is the main challenge in WSN, since the nodes contain smaller size of batteries and battery capacity is bounded. Due to limited energy source, the available energy must be used carefully to prolong the network lifetime. Accordingly, any proposed MAC protocol needs to be energy efficient by minimizing the energy wastes. Always, idle listening causes the most energy unuseful consumption in WSNs. Generally, idle listening happens due to nodes being in a wake mode with no packets forwarded to them, which leads to more energy wastage. Therefore, minimizing idle listening is the key design issue of most MAC protocols.

Generally, in the scheme of the S-MAC and ML-MAC protocols, the nodes are in two states, namely sleep and listen. When the nodes are in a sleep state, they turn off the radio to save energy. The nodes will turn on the radio or turn into listen period when they will send or receive data. This differs from the mechanism of the 802.11 MAC protocol [12], where nodes are always in a state that is idle listening.

Sensor-MAC (S-MAC) protocol [7, 13] is basically a contention-based MAC protocol itself. Contention based achieves its highest performance on periodic traffic applications, the S-MAC protocol overcomes idle listening by setting a node in a listen and sleep state. Each node will turn off the radio in sleep period in order to save energy and will turn the radio back on at listen period for exchanging packets. The duration of listen period (T_listen) is fixed, while the duration of sleep period (T_sleep) depends on the duty-cycle parameters that are previously set. In this protocol, listen period or the radio on is divided into two sub periods, one is for exchanging SYNC packets and the other one is for exchanging data packets as shown in Figure 1.

In the S-MAC protocol, scheduling the radio on or off becomes very important. Each node continuously listens to the channel for at least one listen period plus a sleep period. If the nodes receive SYNC package, then they adopt a schedule carried by the packet. If they do not receive SYNC package, nodes choose their own schedule and follow it. Once a node has a schedule, it will broadcast SYNC packets throughout the whole network. Neighboring nodes will receive SYNC package by adopting a schedule and then continue the deployment of the schedule to the entire network [14, 15]. To save energy, each node is usually in a state of sleep period. The channel seizure may occur in listen period. Node is implicitly synchronized at the beginning of listen period.

In the S-MAC protocol, each node follows the schedule of listen and sleep to reduce the energy consumption. One cycle of the listen period and the sleep period is called a frame. In the S-MAC protocol, there is a duty cycle which is the ratio between the listen period and the frame length.
In the S-MAC protocol with a fixed frame length, listen period value will depend on the parameters of the physical layer and MAC layer. To set the sleep time period, the user can set the value of duty cycle from 1% to 100%.

Energy saving (Es) in the S-MAC protocol is as follows [13]:

$$E_s = \frac{T_{sleep}}{T_{frame}} \quad (1)$$

where $T_{frame} = T_{listen} + T_{sleep}$

$$E_s = \frac{T_{frame} - T_{listen}}{T_{frame}} = 1 - \frac{T_{listen}}{T_{frame}} = 1 - DC \quad (2)$$

where Duty Cycle, $DC = \frac{T_{listen}}{T_{frame}}$

With the equation above, it can be concluded that the energy saving depends on the duty cycle value. The larger the duty cycle value gets, the bigger the energy used and the smaller the energy saving becomes. Therefore, in this paper, the value of duty cycle is 30%.

The ML-MAC [8, 9] protocol is a distributed competition-based MAC protocol that dispenses with any central node to operate the nodes. Generally, it is considered as a modification of the original S-MAC protocol. In this algorithm, the time is divided into frames, and each frame splits into two sessions; wake up session and sleep session. The wake up session is split into L layers as shown in Figure 2.

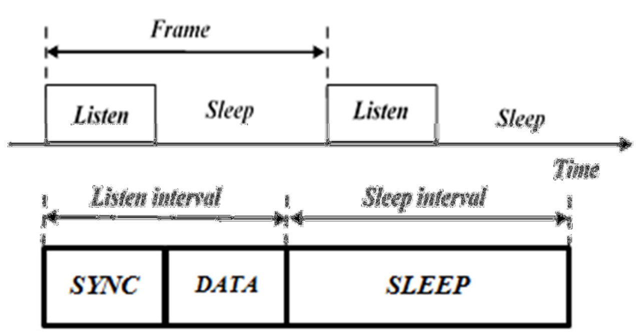

Fig. 1. Frame structure of the S-MAC protocol

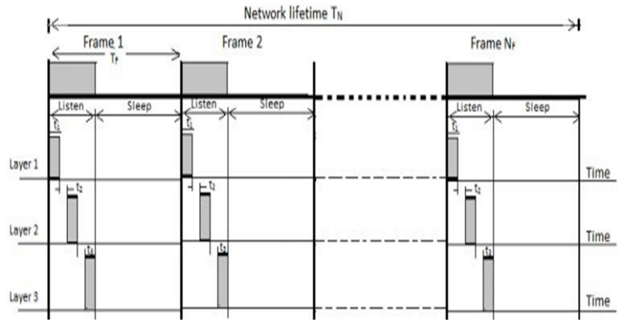

Fig. 2. Design overview of the ML-MAC protocol

Nodes are randomly distributed among this set of layers such that nodes follow a listen/sleep time table in the phases that have been allocated differently from the time tables of the other phases shown in fig. 2. A node in the ML-MAC protocol becomes active according to its allocated phase. Hence, the ML-MAC protocol consumes less energy than that of the S-MAC as the sleep session of a node in the S-MAC protocol is lower than that of a node in the ML-MAC protocol.
L has the following design bounds [8]:

$$\frac{\lambda_{avg}\,(\tau_t+\tau_\rho+2\tau_d+({}^{W}/_{2})\tau_\rho)}{t_1} \leq L \geq \frac{T_f}{t_1+t_2} \quad (3)$$

where L is number of access layers, t_2 is guard time between layers, t_t is Packet transmission delay, τ_d is clock drift delay, λ_{avg} is average message rate per node, T_f is frame duration, t_1 is layer time, τ_p is propagation delay, W is the maximum number of reservation slots.

3. The Proposed Scheme

Firstly, the main contribution of the proposed scheme is minimizing idle listing which leads to maximizing the overall sleep time leading to more energy saving and extending the life time of the network. Generally, the proposed scheme is considered as a modification of the original ML-MAC protocol. Energy efficiency is the main target of the proposed scheme by increasing the average sleep period of the low and medium power nodes. The drawback of existing protocols such as S-MAC and ML-MAC is that they do not take the initial power of each node in the network into consideration.

In the ML-MAC protocol, nodes are distributed among sets of sub layers. These layers have the same duration (t) as shown in figure 3 (i.e. the same wake up). This is not fair, because all nodes will spend the same amount of energy. So, low and medium -power nodes will die faster than high-power nodes. The proposed MAC protocol aims to prolong the life time, especially for low and medium -power nodes by minimizing the energy consumption of them.

The proposed scheme divides all nodes in the network into three groups; low-power nodes, medium power nodes and high-power nodes according to a predefined power threshold. The proposed MAC protocol aims to make the duty cycle of the low and medium -power nodes less than the duty cycle of the high-power nodes. This process reduces the power consumption of the low and medium-power nodes compared to that of high-power nodes. So, the proposed scheme becomes able to extend the overall lifetime of the network compared to those of the S-MAC and ML-MAC protocols.

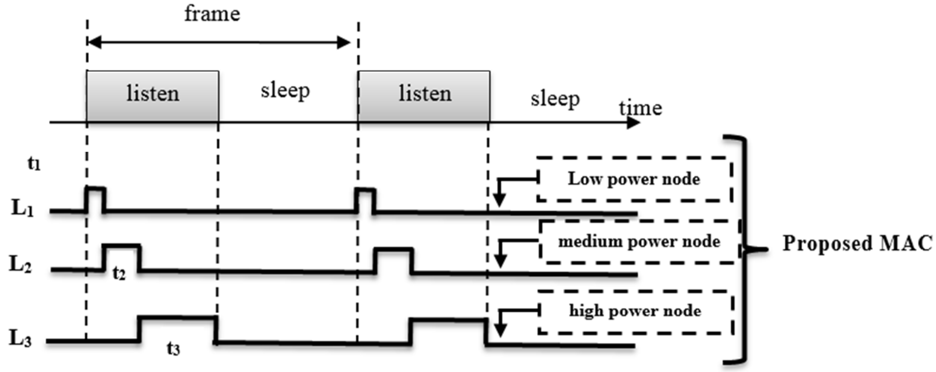

Fig. 3. Design overview of the proposed MAC protocol

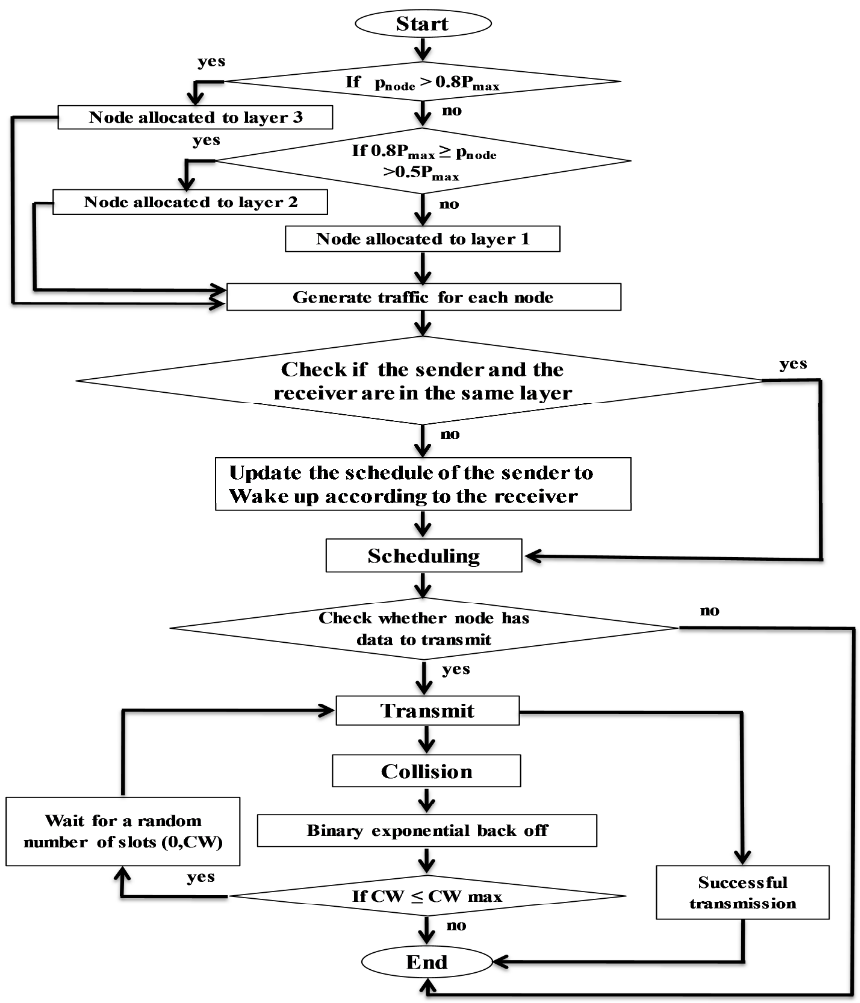

Fig. 4. Flow chart of the proposed MAC protocol

It is a distributed contention-based MAC protocol, where nodes identify their neighbors according to their radio signal strengths. This process is defined as the distribution of contention without a focal node. As figure 3 shows, the time in the proposed scheme is split into frames, and each frame has two intervals; active interval and sopor interval. The active interval has three non-overlapping sub phases, which are not equal in duration, and then nodes are divided between these three sub phases. Nodes in each sub phase obey different listen/sleep time tables. Hence, there is no overlapping between the listen intervals of the nodes in distinct sub layers. Each node in the proposed scheme becomes active at its appointed sub layer.

The flowchart of the proposed algorithm which illustrates the process flow and discrete event is presented in Fig. 4.

Finally, the main achievements of the proposed approach will be clearly illustrated in the next section.

4.1 Simulation Parameters

In this section, we are interested in evaluating our proposed protocols. Let's assume a heterogeneous network which consists of 100 sensor nodes which are randomly deployed in sensing area. The aim of our simulations is to demonstrate the effectiveness of the proposed MAC protocol. We present a comparison between the proposed MAC, S-MAC, and the ML-MAC protocols using the Matlab environment [16]. For executing the simulations of the proposed scheme, the next hypotheses are assumed: -

- A sensor unit is static and it creates messages that follow Poisson distribution.
- The frames produced from splitting the time have listening and sleep durations.
- The operation of a node has three processes; transmit, listen, and sleep.
- Transmitting and receiving buffer sizes in nodes are infinite.
- All-MAC procedures depend on the IEEE 802.11[12].
- It is alleged that the wireless channel is perfect. There are no channel impairments.
- The radio unit of the node is TR 1000 from RF Monolithic [17]. This transceiver consumes power in transmitting, listening, and sleeping procedures which are 24.75 mW, 13.5 mW, and 15 µW, respectively. The data rates of transmitter and receiver are equal to 19.2 Kbps.

Simulation parameters are presented in Table 1. To make the simulation simpler, firstly the traffic is generated at the start of the simulation for all the nodes for the entire simulation time. Each packet generated is stocked in the node transmit buffer and is assigned three flags; arrival time, receiving node address, and appointed slot address. Calculating the time and the energy required to send that message to its destination is performed using these flags. The advancement of a time indicator and examination for packets anatomize the traffic until the end of the emulation. In emulation, the time indicator is defined to be frame time/1000, i.e., frames consists of 1000 slots. So, each slot duration equals 1ms. The total amount of consumed energy by each node during the whole emulation duration is specified by equation 7. The data packet takes 20 ms to transmit in an exemplary transceiver channel. The results are presented in figures (6) to (15). The power threshold (P_{th}) is illustrated in Table 1. These values of threshold power and layer duration have been chosen according to experimenting different values. Then values that have improved energy consumption without more serious delay have been chosen.

$$E_n = (T_{transmit} \times P_{transmit}) + (T_{listen} \times P_{listen}) + (T_{sleep} \times P_{sleep}) \quad (4)$$

Table 1
The simulation parameters [8]

Parameter		*Value*
Average packet inter-arrival time, T		*2-11 s*
Number of frames, N_F		*2000*
Simulation time		*2000 s*
Number of layers (ML-MAC), L		*3*
Number of nodes, N		*100*
Frame duration, T_F		*1 s*
Listen time for S-MAC, T_{listen}		*0.3 s*
Sublayer duration, (t) for ML-MAC		*0.3/3 s*
Low power node sublayer time (t_1)		*0.1 T_{listen}*
medium power node sublayer time (t_2)		*0.2 T_{listen}*
high power node sublayer time (t_3)		*0.7T_{listen}*
Node sleeping power		*15 µW*
Node listening power		*13.5 mW*
Node transmitting power		*24.75 mW*
Number of initial reservation slots, W		*8*
Power threshold	*Low power nodes*	*$P_{th} \leq 0.5\ P_{n\text{-}max}$*
	Medium power nodes	*$0.8P_{n\text{-}max} \geq P_{th} > 0.5\ P_{n\text{-}max}$*
	High power nodes	*$P_{th} > 0.8\ P_{n\text{-}max}$*
Node transmission data rate		*19.2 kbps*
Average packet length, α		*38 Bytes*

4.2 Simulation Results

The most important metrics used in order to evaluate the performance of our contribution are:
(i) Average energy consumption per node calculated as the total energy consumed / total number of sensor nodes according to the next equation.

$$E_{avg} = \frac{\sum_{n=1}^{N} E_n}{N} \tag{5}$$

(ii) Average packet latency. It is defined as the average time taken by the packets to reach the receiving node.

D(i) = the packet receiving time – the packet generation time, or, $T_r - T_g$ (6)

$D_{avg} = \frac{\sum_{i=1}^{N_p} D(i)}{N_p}$ where N_p: number of packet (7)

❖ **Coherent Mode.**

The transmitting and receiving nodes must communicate with each other in the same layer (wake up together), this is the meaning of the coherent mode. Here, is a study of a variety of performance evaluation parameters such as energy consumption, delay, and collision probability.

The proposed MAC protocol significantly reduces the energy consumption more efficiently than the S-MAC and the ML-MAC protocols. Figure 5 presents the overall energy consumption for every node for the S-MAC, ML-MAC, and the proposed MAC. It confirms that the proposed MAC protocol expends 73% less energy than the S-MAC protocol and 23.1% less energy than the ML-MAC protocol, because the listing period of the proposed MAC protocol is shorter than that of both the S-MAC and ML-MAC protocol, which leads to a reduction in energy consumption.

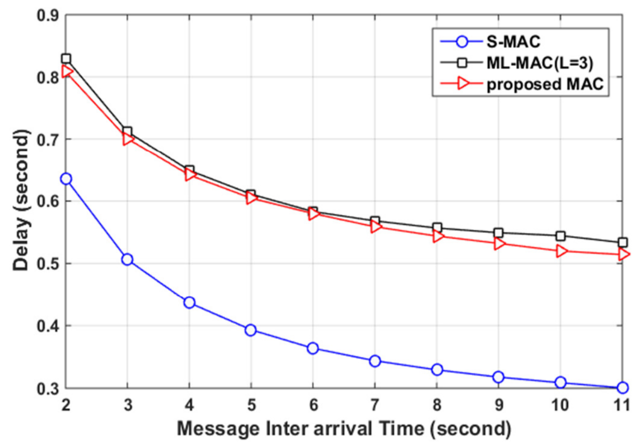

Fig. 5. Average energy consumption node for the S-MAC, ML-MAC and the proposed MAC protocols

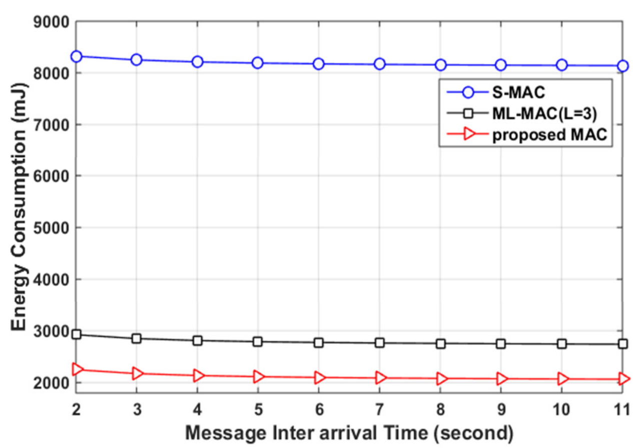

Fig. 6. Average delay for all packets sent for the S-MAC, ML-MAC and the proposed MAC protocols

The proposed MAC protocol slightly increases the delay because the nodes are in sleep mode for longer durations as shown in fig 7. Figure 6 presents an average latency for all packets transmitted by the S-MAC, ML-MAC, and the proposed MAC protocols. The proposed MAC protocol increases delay by 32.2% more than that of the S-MAC protocol and decreases delay by 2.8% less than that of the ML-MAC protocol

The proposed MAC protocol achieves the highest percentage sleep time up to about 92.5%. On the other hand, the ML-MAC protocol produces a percentage sleep time of about 90%, while the S-MAC protocol produces a percentage sleep time of about 70%. Figure 7 presents the percentage of the period that each node sleeps for the S-MAC, ML-MAC and the proposed MAC protocols.

From figures 5 and 7, in general, it is clear that the improvement rate in energy consumption is higher than the degradation rate in the delay. The proposed MAC protocol slightly increases collision probability as the nodes sleep more here compared to the S-MAC and the ML-MAC protocols.

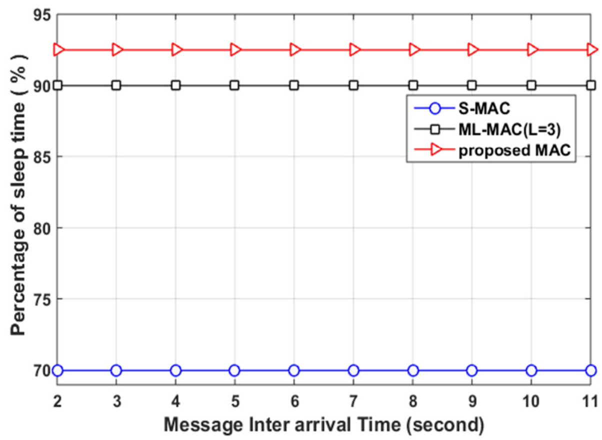

Fig. 7. Average percentage of time when a node is in the sleep state for the S-MAC, ML-MAC and the proposed MAC protocols.

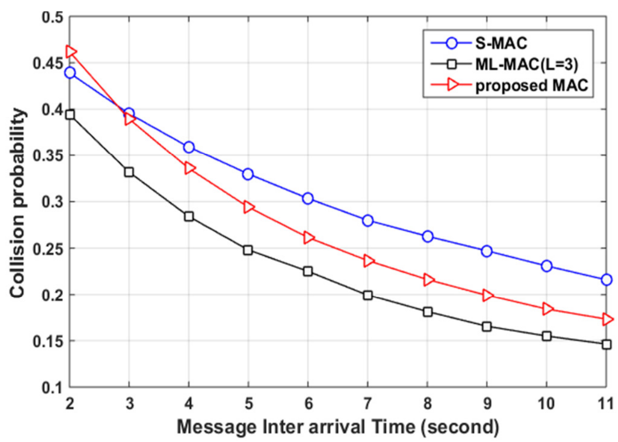

Fig. 8. Probability of collision for the S-MAC, ML-MAC and the proposed MAC protocols.

Figure 8 presents the probability of collision for the S-MAC, ML-MAC, and the proposed MAC protocols. Generally, when traffic is dense, i.e., the packet inter-arrival time is lower than about 5 s, more packets are generated, and hence collision probability for three protocols become high and it drops dramatically by increasing the inter-arrival time as collision probability is reduced for light traffic. If the packet inter-arrival time is above 5s, then traffic is light, and fewer packets are generated.

All these results are illustrated in Figure 9, taken at an inter-arrival time (t) =2. Figure 9 presents the average energy consumption per low power nodes, medium power nodes, and high power nodes for the S-MAC, ML-MAC, and the proposed MAC protocols. It is clear that energy consumption of low, medium and high power nodes is the same in the ML-MAC and the S-MAC protocols. The proposed MAC protocol makes energy consumption of low and medium power nodes less than energy consumption of high power nodes by adapting layer duration, which leads to maximizing lifetime of the network.

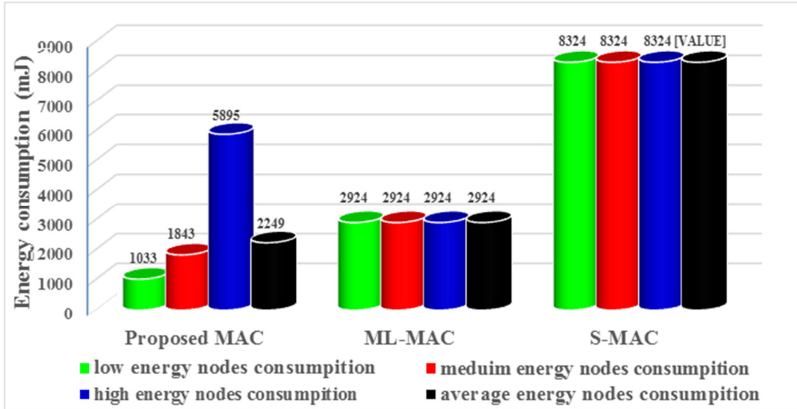

Fig. 9. Average energy consumption per low-, medium-, and high power nodes for the S-MAC, ML-MAC and the proposed MAC protocols.

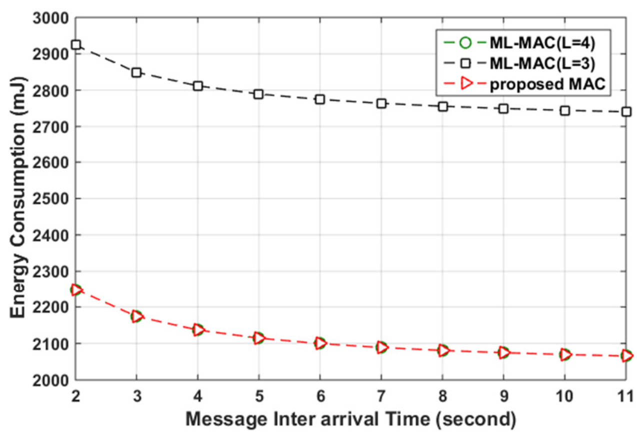

Fig. 10. Average energy consumption per node for the ML-MAC (L=3&L=4) and the proposed MAC protocols.

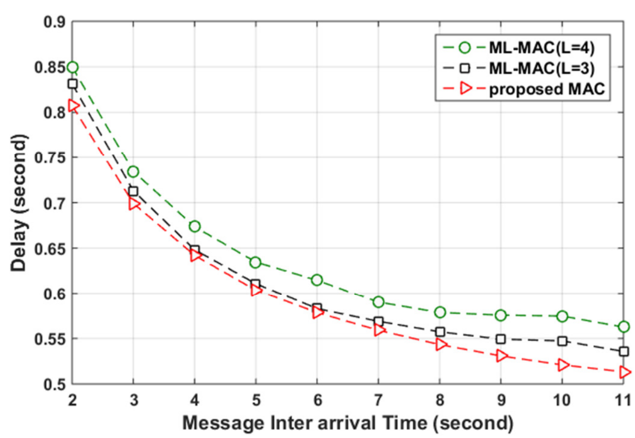

Fig. 11. Average delay for all packets sent for the ML-MAC (L=3&L=4) and the proposed MAC protocols.

As shown in figure 10, the proposed MAC protocol with only three layers' duration provides the same power saving compared to the ML-MAC protocol using four layers. It is clear that the proposed MAC protocol outperforms the ML-MAC protocol whether it has three or four layers.

This means that the proposed MAC protocol is able to provide a better performance than the ML-MAC protocol with a smaller number of layers (lower complexity). Figure 11 presents an average delay for all packets sent. It is clear that the proposed MAC protocol uses three adaptive layers. It provides the same energy consumption, but also less delay in comparison with the ML-MAC protocol using four layers.

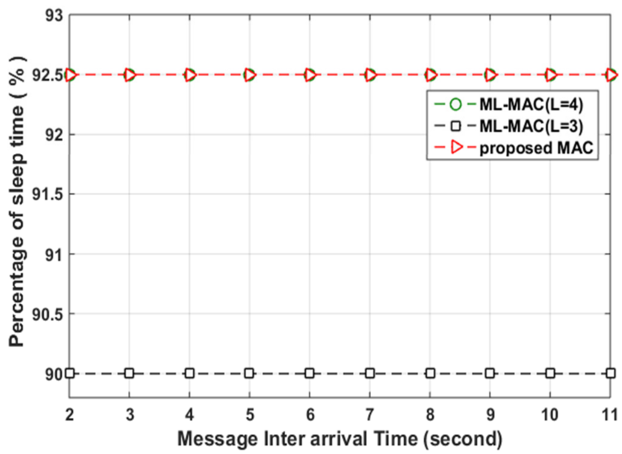

Fig. 12. Average percentage of time when a node is in the sleep state for the ML-MAC (L=3&L=4) and the proposed MAC protocols

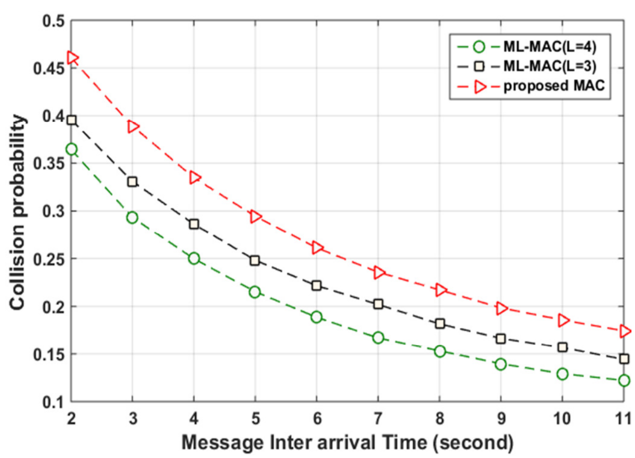

Fig. 13. Probability of collision for the ML-MAC (L=3&L=4) and the proposed MAC protocols

As shown in figure 12, nodes in the proposed MAC protocol spend the same time in sleep mode compared to the ML-MAC protocol using four layers, which produces the same power saving. Figure 13 presents the probability of collision for the ML-MAC protocol, whether it has three or four layers and the proposed MAC protocol. It shows that the probability of collision is slightly increased by a small amount.

6. Conclusion

There are many reasons for power dissipation such as idle listening, when a node becomes in receiving mode for possible traffic. Due to node power constraint the energy conservation becomes the main challenge during WSN implementation. A large number of MAC protocols have been suggested by researchers, but all existing solutions have a drawback of unfair energy consumption between nodes, which leads to fast die of low and medium power nodes. For fair energy consumption between nodes, this paper presented a new scheme based on initial power for each node.

The proposed algorithm reduces the energy consumption for low-power nodes. It classifies nodes into three groups depending on a specific power threshold, and then the three groups of nodes are distributed among sub layers. The low-power nodes work with short layer durations, the medium-power nodes work with moderate layer durations, and the high-power nodes work with larger layer durations so as to lessen the idle listening time. The emulation results have shown that the proposed MAC protocol saves energy more than both the S-MAC and ML-MAC protocols. In coherent mode the proposed protocol saves 73% and 23.1% of the energy compared to the S-MAC and ML-MAC protocols, respectively. Finally, by simulation and results comparison, it is clear that the proposed MAC protocol is more energy efficient.

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