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Slotted ALOHA Based p-Persistent CSMA Energy-Efficient MAC Protocol for WSNs

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Abstract: Extending the lifetime of wireless sensor networks (WSNs) is considered a vital challenge due to its limited sources, small size, and difficulty in replacing the battery when used to monitor remote areas. Various approaches and protocols have been proposed to reduce energy consumption. Medium Access Control (MAC) particularly random-access protocols are important techniques used to extend network lifetime and reduce energy consumption. In this paper, we proposed an improvement on the slotted ALOHA protocol using p-persistent carrier sense multiple access (CSMA) protocol. The channel divided into slots as in the slotted ALOHA, the distinction being that the slots have an adaptive duration based on the size of the data and do not impose the node to send at the beginning of the slot. In addition, the nodes sense the channel if it is idle or busy using the P-persistent CSMA approach before beginning the data transmission. The performance of pure ALOHA, slotted ALOHA, p-persistent CSMA, S-MAC, and T-MAC protocols was evaluated separately and compared to the proposed protocol. The simulation results show that the proposed protocol reducing energy consumption significantly hence increases the network lifetime.

Keywords: Wireless Sensor Networks (WSNs), Medium Access Control (MAC), Energy Efficient, p-Persistent CSMA, Slotted ALOHA, S-MAC, T-MAC.

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1. INTRODUCTION

The growing role of wireless sensor networks (WSNs) and their widespread use in many environmental monitoring applications such as disaster management, military, battlefield, security, and many more to detect phenomena in unreachable areas have made it a major research topic. WSN consists of a collection of self-organizing wireless sensor nodes. These sensor nodes are characterized by limited energy, low cost, small size, and battery-operated. WSN generally suffers from many issues and challenges, such as ad hoc deployment, secure localization, network topology, data gathering, fault tolerance, power consumption, cost of production, hardware design, computational power, and memory size, etc. [1], [2], [3], [4].

This paper dealt with the issue of power consumption. Sources of energy consumption in WSN are represented in sensing, processing, transmitting, receiving, collision, etc. The impossibility or unprofitability of replacing batteries forced authors to propose energy-efficient protocols to reduce energy consumption, thereby prolonging the lifetime of the network.

Medium Access Control (MAC) protocols in WSN play an important role in energy conservation as the maximum power consumption occurs in data transmission and receiving processes [5] and the control of the transceiver is the responsibility of the MAC layer. Generally, multiple-access protocols classified into random access protocols, controlled access protocols, and channelization protocols [6].

This paper focused on random access protocols where the problem of slotted ALOHA is addressed, which obliges the station to send data solely at the start of the time slot using the p-persistent carrier sense multiple access (CSMA) channel sensing method in order to reduce collisions, reduce power consumption and hence extend the lifetime of the WSN. The performance of the proposed protocol is measured by the number of alive nodes, the lifetime of the network, the stability of the network, the amount of energy consumption compared to pure ALOHA, slotted ALOHA, p-persistent CSMA, S-MAC, and T-MAC protocols.

The rest of the paper is organized as follows: Section 2 presents the related work on energy-efficient MAC protocols. Section 3 gives an overview of random access protocols. Section 4 explains the model of the system.

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Section 5 details the proposed protocol. The results of the simulation and the comparison are evaluated in Section 6. Subsequently, the paper is concluded in Section 7.

2. RELATED WORK

The significant role of MAC protocols in saving energy and increasing network lifetime has led researchers to develop and propose a large number of energy-efficient MAC protocols. In [7], Wei Ye et al. proposed the Sleep MAC (S-MAC) protocol for wireless sensor networks to reduce energy consumption and avoid collisions.

Tijs van Dam et al. resolved the issue of idle listening in WSN by submitting the Timeout MAC (T-MAC) protocol. The T-MAC protocol adjusts the listening/sleeping cycle dynamically using timeout intervals (TA) which, in turn, reduces energy consumption [8].

In [9], Bulent Tavli and Wendi B. Heinzelman have presented the Time Reservation Using Adaptive Control for Energy Efficiency (TRACE) protocol, described it in detail, and estimated its performance throughput the theoretical analysis and computer simulations in 2003. Multi-Hop Time Reservation Using Adaptive Control for Energy Efficiency (MH-TRACE) MAC protocol was proposed in 2004 for broadcasting packets in a multi-hop radio network [10].

The authors in [11] suggested an asynchronous wise-MAC (Wireless Sensor MAC) protocol based on a preamble sampling mechanism. Venkatesh Rajendran et al. [12] submitted an energy-efficient collision-free TRAMA (Traffic Adaptive Medium Access) protocol to reduce energy consumption by ensuring that unicast and broadcast transmissions do not cause collisions and allowing nodes to assume a low-power idle state when they are not being sent or received. The authors of [13] produced a Routing Enhanced MAC (R-MAC) protocol that improves energy efficiency through the use of duty cycles, reduces end-to-end latency, and decreases node contention.

The authors in [14] proposed ALOHA with Collision Avoidance (ALOHA-CA) and ALOHA with Advance Notification (ALOHA-AN) inspired by ALOHA for underwater acoustic WSN to increase throughput and reduce collision that would prolong the lifetime of the network. In [15], the authors suggested a distributed slotted ALOHA, which relies on the number of neighbor nodes to dynamically change the number of active TDMA slots in order to increase throughput and decrease energy consumption.

3. RANDOM ACCESS PROTOCOLS

A. Pure ALOHA

Pure ALOHA is a single-hop system that is considered to be the basis of the ALOHA family. It's characterized by its simplicity. In Pure ALOHA, multiple stations share one channel. The station has no constraint on its transmission. When a station has a frame ready to transmit, it sends it directly without checking the status of the channel, it is free or busy. The possibility of collision is therefore very high in the pure ALOHA protocol [16], [17]. After sending the frame, the station waits to receive an acknowledgment from the destination. If no acknowledgment was received during the Round Trip Time (RTT) period, the station assumes a collision occurred, the frame was lost or destroyed, and attempts to retransmit the frame after waiting for a random time (Back-off Time) [18].

B. Slotted ALOHA

The shared channel is divided into T_{fr} slots in the Slotted ALOHA. Slotted ALOHA, other than pure ALOHA, when a station has a frame ready to send, does not send it directly. The station can only send its frame at the beginning of the slot time. As a result, the probability of collisions occurring is reduced compared to pure ALOHA, which in turn increases efficiency [16], [18], [19]. The procedure for slotted ALOHA is clarified in Fig. 1.

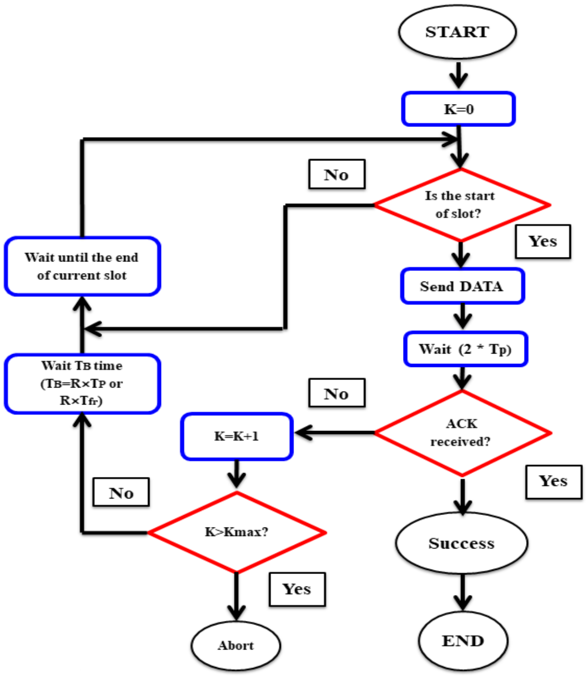

Figure 1. Flowchart of slotted ALOHA protocol

Where:
K: Number of attempts.
K_{max}: Maximum number of attempts initially is 15.
T_{fr}: Average transmission time.
T_P: Maximum propagation time.
T_B: Back-off time = $R \times T_{fr}$ or $R \times T_P$

R: Random number = 0 to $2^K - 1$

C. *Carrier Sense Multiple Access (CSMA)*

The CSMA protocol has been advanced in order to reduce collisions and improve network performance. The station senses the channel to check if it is idly before sending a frame. In general, there are two mechanisms for the sensing of the carrier: the physical and virtual carrier sense. Either a station that physically senses the channel as in the physical carrier sense or gets the information from the frame headers in the case of a virtual carrier sense [20]. There are three methods of persistence to inform the station of what to do if the channel is busy or idle [18], [21]: 1-persistent, non-persistent and p-persistent methods.

The p-persistent method used when the channel contains time slots, the duration of the slots is equal to or greater than the TP (maximum propagation time). The p-persistent combines the advantages of 1-persistent and non-persistent methods to reduce collisions and improve efficiency. When the station is ready to send data, the channel is checked for busy or idle. If the channel finds idle:

1- With a probability p, the station transmits its frame.

2- With a probability of q = 1 − p, the station stops until the beginning of the next time slot and senses the channel again.

a. If the channel is idle, Step 1 is repeated.

b. If the channel is busy, it behaves as if there was a collision and the back-off process is applied.

4. SYSTEM MODELS

A. *Energy Model*

This paper uses the classic energy model shown in Fig. 2 [22]. The energy consumption for transmitting and receiving k bits can be calculated using equation (1) and equation (2) [23]:

$$E_{TX}(k, d) = E_{elec} \times k + \varepsilon_{amp} \times k \times d^2 \qquad (1)$$

$$E_{RX}(k) = E_{elec} \times k \qquad (2)$$

Where:
E_{TX}: The energy needed to transmit one packet of bits.
E_{RX}: The energy needed to receive one packet of bits.

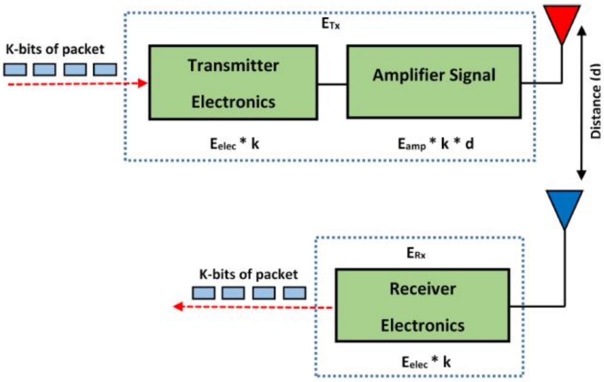

Figure 2. The wireless sensor network energy model

E_{elec}: Energy expended during modulation or demodulation.
ε_{amp}: The energy dissipated by the amplifier.
k: The number of bits in a packet.
d: The distance from the source to the destination.

B. *Network Model*

First Scenario: The proposed protocol is applied to the sensing field with area 60 × 60 m^2. Eighty sensor nodes are distributed manually in the sensing area. There are two types of sensor nodes deployed, Normal Node (NN) and Cluster Head (CH). The distance between nodes is fixed at a distance of 5 m. The sensor area consists of 8 CHs and 72 NNs. The CH positions are (10, 10), (50, 10), (20, 20), (40, 20), (20, 40), (40, 40), (10, 50), and (50, 50) respectively. The main responsibility of the normal nodes is to sense the event and send it to the cluster head. The cluster head, in turn, aggregates and processes the data for normal nodes and transmits it to the Base Station (BS) located at the center of the sensing field as shown in Fig. 3.

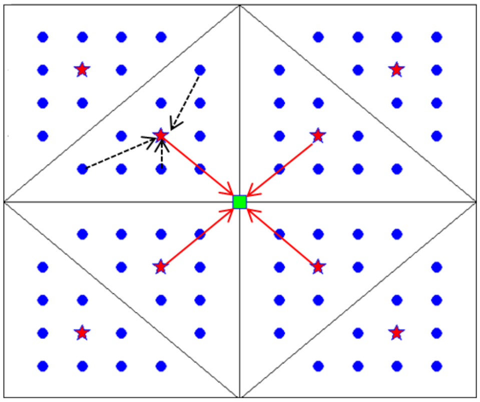

Figure 3. Sensor scope of the first scenario

● **NN** ★ **CH** 🟩 **BS**

Second Scenario: In this scenario, the proposed protocol was operated under conditions similar to the network conditions used in [24] in order to provide a fair comparison between the proposed protocol and the protocols referred to in [24]. The proposed protocol is applied to 10 sensor nodes randomly dispersed in the 100 × 100 m^2 area sensor field. When an event occurs, the sensor node detects the event and transmits it directly to the BS located at the center of the sensor scope as shown in Fig. 4.

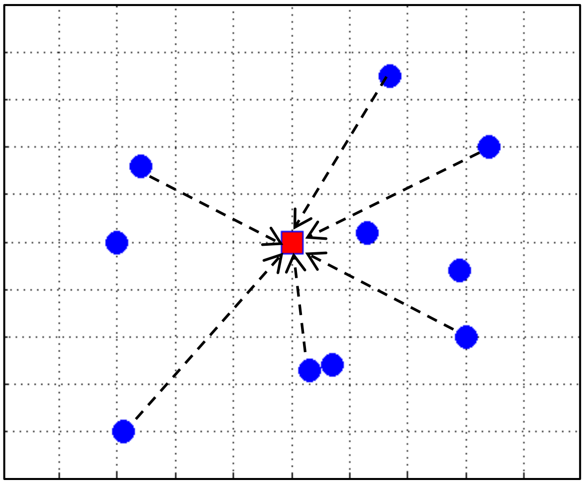

Figure 4. Sensor scope of the second scenario

5. PROPOSED PROTOCOL

The proposed protocol is a development based on the slotted ALOHA protocol to reduce collision potential, minimize energy consumption, and maximize network lifetime. The IEEE 802.11b standard has been used for the proposed protocol. The proposed protocol consists of two parts, the first part used to transmit the sensed data from the normal nodes to the cluster head. The second part used to transmit the collected data to the base station via the cluster head.

The data collection process is divided into rounds, and each round is divided into two phases: the set-up phase and the steady-state phase. In the set-up phase, after nodes are manually deployed in the sensing field, each CH transmits an announcement message to all nodes within its transmission range. The announcement messages include the location of the CH, the number of members it has, and its distance from BS. The NNs decide which cluster to join, depending on the Received Signal Strength Indicator (RSSI) of the announcement message. In the steady-state phase, the cluster heads collect data from normal nodes and transmit it to the base station.

In the first scenario, every normal node follows the flow chart in Fig. 5 to transmit the sensed data to the cluster head at each round. Time is divided into slots, as in the slotted ALOHA, but the slot time is not fixed and varies depending on the size of the data. Random numbers (r) generated between (0) and (1) at the beginning of each round. Each normal node in a specific cluster shall take a random number. When the normal node has data ready to be transmitted, the channel is first checked for busy or idle. If a channel is found free, it will compare its random number (r) with the threshold value (P-threshold) calculated in equation (3). Only a node with a larger r value and less than the P-threshold (Preventing competition between nodes and thereby reducing collision) will seize the channel and transmit its data size to the cluster head to allocate time depending on the size of the data. After time allocated, the normal node will start transmitting its data and waiting for the round-trip time (RTT: the time required to transmit data to the destination node plus the time required to receive an acknowledgment from the source node) to receive an acknowledgment that tells the normal node that the data was received successfully. In case no acknowledgment has been received, the normal node will assume a collision occurred and try to transmit the frame again after waiting for the start of the next slot time and back-off time.

$$\text{P-threshold} = (1 - (1/N)) \wedge (N - 1) \quad (3)$$

Where: N represents the number of normal nodes in the cluster.

After receiving the frame successfully through the cluster head, the cluster head will use a non-persistent multi-channel method to transmit the collected data to the base station in order to avoid collision and the process of retransmits the frame, all of which consume additional energy. The sensor field is divided into four regions, as shown in Fig. 6. Each region uses one of the IEEE 802.11b non-overlapping channels (1, 5, 9, and 13) for data transmission [25]. When a specific cluster head has a frame to send it first checks its position if it locates at region (1) it senses the channel (1) if it finds the channel idle, it transmits the frame directly, otherwise, it will sense the channel again after waiting for a random amount of time. If it locates at region (2) it senses the channel (5) if it finds the channel idle, it transmits the frame directly, and otherwise, it will sense the channel again after waiting for a random amount of time. If it locates at region (3) it senses the channel (9) if it finds the channel idle, it transmits the frame directly, and otherwise, it will sense the channel again after waiting for a random amount of time. If it locates at region (4) it senses the channel (13) if it finds the channel idle, it transmits the frame directly, and otherwise, it will sense the channel again after waiting for a random amount of time.

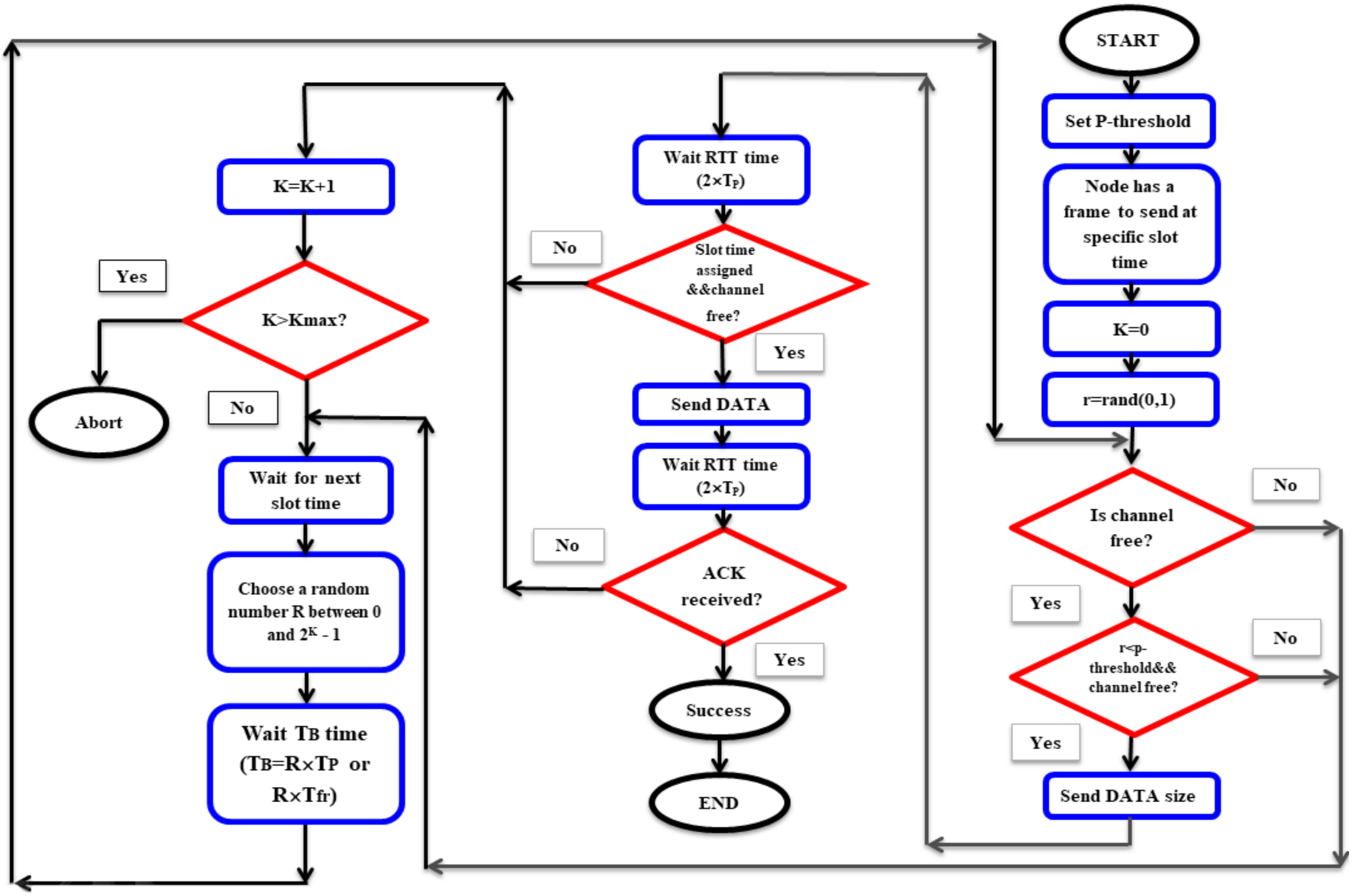

Figure 5. Flowchart of proposed protocol to send data from NN to CH

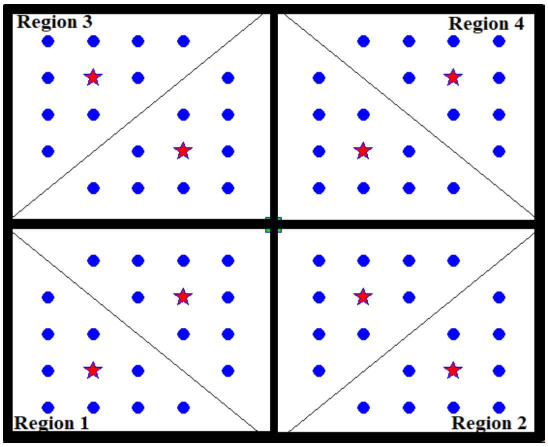

Figure 6. Sensor field's regions

In the second scenario, ten nodes are randomly separated in 100 × 100 m^2 area. The nodes in the network follow the flowchart in Fig. 5 to transmit the sensed data directly to BS.

6. SIMULATION AND RESULTS

In order to evaluate the performance of the proposed protocol, a comparison is made with pure ALOHA, slotted ALOHA, p-persistent CSMA, S-MAC, and T-MAC protocols using MATLAB emulation. The proposed protocol aims to prolong the lifetime of the network by reducing collisions and improving energy consumption. There are several metrics used to evaluate the performance of the network. The following metrics are used in this paper:

- **Alive Nodes:** Represents the number of nodes that stay alive in each round.
- **Network lifetime:** Represents the period from the start of the working time of the network to the death of the last node in the network measured in the number of rounds.

- **Stability:** Represents the period from the start of the working time of the network to the death of the first node in the network measured in the number of rounds.
- **Energy Consumption:** Represents the amount of energy consumption in the network over a specific time period.

Table I. shows the parameters used in the simulation.

First scenario: In this scenario, the performance of the proposed protocol is evaluated against pure ALOHA, slotted ALOHA, and p-persistent CSMA protocols in terms of the number of alive nodes. As shown in Fig. 7, the proposed protocol significantly exceeds the other protocols due to the weaknesses of the other protocols. The reason for the rapid death of nodes in pure ALOHA is the high probability of collision, each node having a frame transmits it directly without taking into account that the other nodes may have frames to transmit at the same time. In the slotted ALOHA, the channel is divided into slots and the node can transmit only at the beginning of the slot, the probability of collision reduced compared to pure ALOHA, but still high, resulting in a severe decrease in the number of alive nodes. In the P-persistent CSMA, the node checks the channel to be busy or idle before the frame is transmitted. The possibility of a collision is reduced, but cannot be eliminated. The node can sense the channel and detect it idle only because the first bit transmitted by another node has not yet been received. In the proposed protocol, the collision in a specific cluster is eliminated by obliging only one node with a maximum *r* value less than the P-threshold to be transmitted in a round. On the other hand, the transmission of data from CH to BS via multi-channel reduces the contention on a single channel, reduces the collision, and therefore saves a large amount of energy. As a result, the proposed protocol keeps the node alive for a long time, reduces energy consumption, and therefore increases the lifetime of the network compared to other protocols.

TABLE I. Simulation parameters

Parameters	First Scenario	Second Scenario
Simulation area	60 × 60 m^2	100 × 100 m^2
Base station position	(30,30)	(50,50)
Number of nodes	80	10
Number of CH	8	-
Number of NN	72	10
Initial energy of CH	0.5J	-
Initial energy of NN	0.0025J	1000J
ε_{amp}	100pJ/bit/m^2	100pJ/bit/m^2
E_{elec}	50nJ/bit	50nJ/bit
Packet size	2000bit	4096bit

Fig. 8 displays the death of the first and last nodes in each protocol. The first node died in pure ALOHA in round 20, and the last node died in round 391. The first and last nodes died in slotted ALOHA in rounds 26 and 427, respectively. In the p-persistent CSMA, the first and last nodes died in rounds 35 and 472, respectively. In the case of the proposed protocol, the first node died in round 4454 but was not determined when the last node died due to the difficulty of running the code for a long time. As shown in Fig. 8, the proposed protocol significantly prolongs the lifetime of the network compared to other protocols.

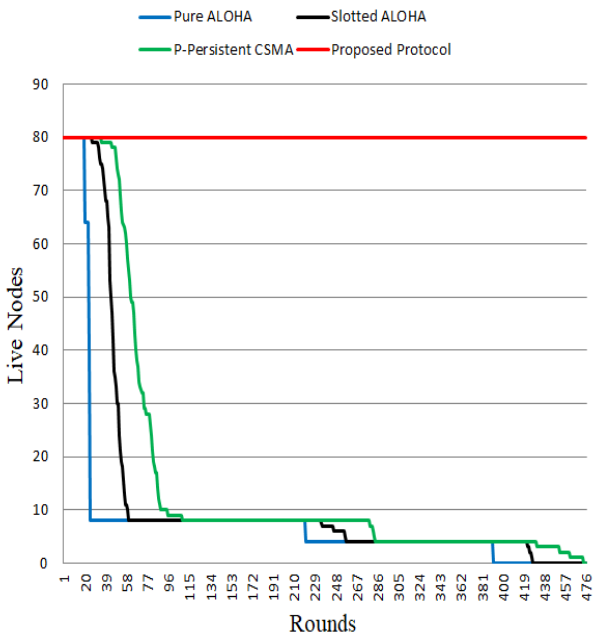

Figure 7. Number of alive nodes per round

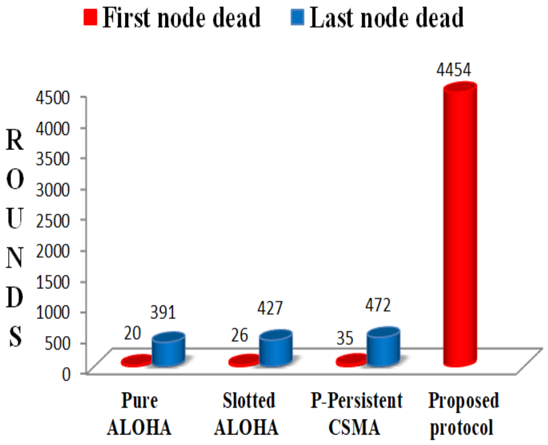

Figure 8. First node dead versus last node dead

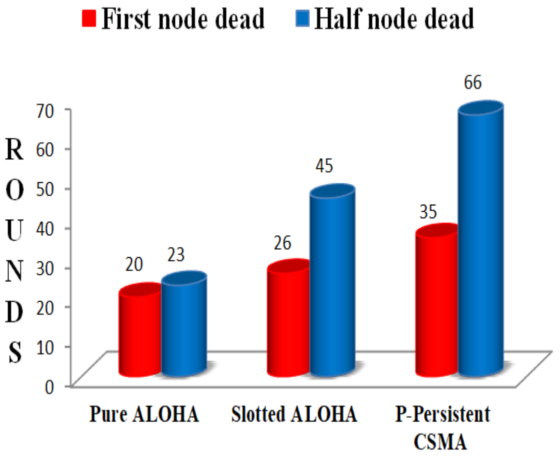

Figure 9. Network stability in pure ALOHA, slotted ALOHA, and p-persistent CSMA protocols

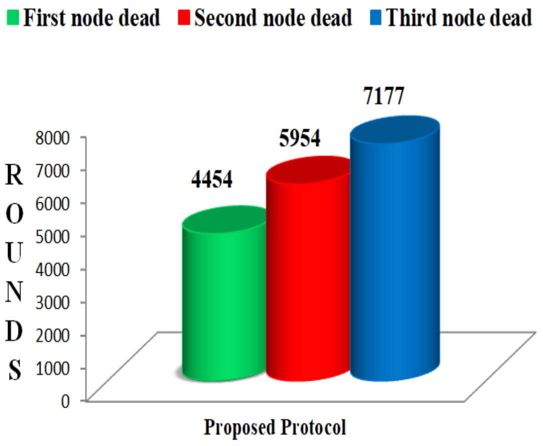

Figure 10. Network stability in the proposed protocol

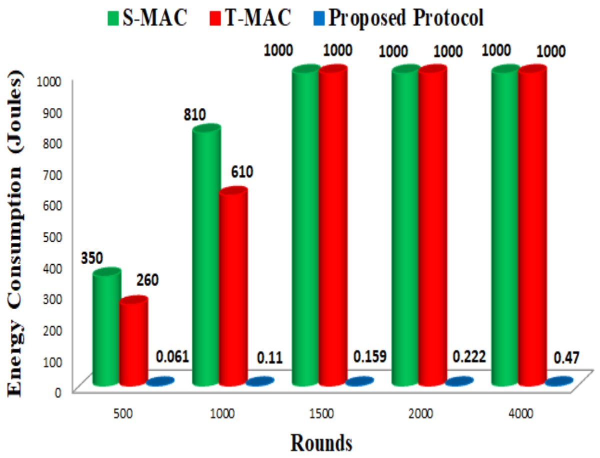

Figure 11. Energy consumption comparison of S-MAC, T-MAC, and proposed protocol

As shown in Fig. 9 and Fig. 10, the network remained stable until round 20, 26, 35, and 4454 in pure ALOHA, slotted ALOHA, p-persistent CSMA, and proposed protocol. Where the results have shown that the proposed protocol is more stable than other protocols.

Fig. 11 shows the results of the second scenario in which the performance of the proposed protocol was compared with the simulation results of the S-MAC and T-MAC protocols [24] in terms of energy consumption. As illustrated in Fig. 11, the proposed protocol consumes much less energy than the S-MAC and T-MAC protocols. The reasons that make the proposed protocol much better than other protocols are that the nodes are treated as a single cluster in which the collision is eliminated by allowing only one node with a maximum *r* value less than the P-threshold to be transmitted in a round. Elimination of idle listening that other protocols suffer, nodes switch off their transceiver when they do not have data to send all the time, and when they have data ready for transmission, use the p-persistent CSMA method to check the channel if it is idle or busy before the transmission starts. Eliminate the process of exchanging synchronous packets, such as ACK and RTS / CTS packets, which consume a large amount of energy. As a result, the proposed protocol consumes much less energy than other protocols, thus extending the lifetime of the proposed protocol.

7. CONCLUSION

The main aim of this paper is to propose an energy-efficient MAC protocol to minimize energy consumption, minimize collisions, minimize idle listening and therefore extend the lifetime of the network. The proposed protocol combines the advantages of both the slotted ALOHA and the p-persistent CSMA protocols. The channel divided into slots as in the slotted ALOHA, the difference is that the slots have an adaptive length depending on the size of the data and do not force the node to send at the start of the slot. In addition, the nodes sense the channel using the P-persistent CSMA method before starting the data transmission. The simulation results show that the proposed protocol is more efficient than pure ALOHA, slotted ALOHA, p-persistent CSMA, S-MAC, and T-MAC in terms of the number of alive nodes, network lifetime, network stability, and energy consumption.

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