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A Novel Adaptive MAC protocol for Energy Efficient Wireless Sensor Networks

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Abstract: Since each sensor node in the Wireless Sensor Network operates with a battery of limited power, energy efficiency in the sensor network is an important issue. Therefore, by reducing the energy consumption of the sensor nodes, the overall network lifespan of the sensor network can be maximized. Various protocols have been proposed in the MAC layer by researchers. In this paper, an energy-efficient adaptive buffer threshold MAC (AB-MAC) has been proposed, to improve the energy efficiency of sensor networks without affecting the average latency. The protocol sets a buffer threshold for each node, which determines whether data is to be transmitted or not. The threshold will be set differentially according to the distance between the sink and the transmitting node, thereby reducing the energy consumption of the node and greatly improving the energy efficiency of the entire network. In addition, to reduce the transmission delay time, the data transmission will be performed according to the priority of sensed data. The performance evaluation is done through MATLAB, the proposed protocol is compared with the S-MAC and T-MAC protocols, it was confirmed that the proposed technique improved the data transmission time and energy efficiency, hence extended the network lifespan.

Keywords: Wireless Sensor Network (WSN), MAC protocol, Transmission latency, S-MAC, T-MAC.

1. Introduction

The sensor network is being used in various fields to collect remote information through a sensor with a multi-functionality of autonomous network arrangement with a large number of sensor nodes. The wireless sensor network is mainly composed of three parts: nodes, gateways and software. Spatially distributed measurement nodes monitor the surrounding environment by connecting with sensors [1]. The monitored data is sent to the Sink node wirelessly as shown in the Figure 1 and the sink node can be connected to a wired system, so that the software can be used to collect, process, analyze and display the data. A router is a special measuring node, you can use it to extend the distance and increase reliability in WSN.

The emergence of wireless sensor networks has aroused widespread concern all over the world. The earliest research on wireless sensor network technology was initiated by the US military in the 1990s, which started research projects such as REMBASS, TRSS, SSW, SensorlT, WINS, Smart Dust, SeaWeb, and NEST. Since then, the National Natural Science Foundation of the United States has established a large number of related projects, such as FireBug, CENS, and so on. Companies such as Crossbow, DustNetwork, Ember, Chips, Intel, Freescalc in the United States, Philips, Siemens, Nihonga, Ericsson, ZMD, France Telecom, Chipcon and other companies in the EU, and NEC, OKI, Skyley Networks, OMRON have started developing the products. In addition to the research of WSN, international standards related to WSN have also been released one after another, such as IEEE802.15.4 [2], Wireless HART [3], 6Lowpan [4]/ISA100[5]. With the continuous maturity of wireless sensor network theory and technology, its applications have already expanded from the military /national defence fields to environmental monitoring, traffic management, medical health, business services, anti-terrorism, disaster relief, and many other fields, enabling people a large amount of accurate and reliable information of environment be obtained at any time, any place. and it will eventually become a reliable sensing technology. And hence Wireless Sensor Networks can be said to be a core technology to build a future of environmental monitoring.

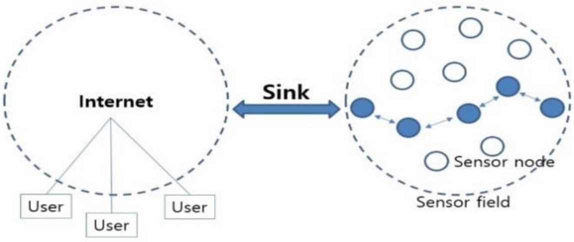

Fig.1. Wireless Sensor Network Architecture.

Since the huge number of sensor nodes are difficult to maintain and operate with limited energy, due to their extremely small size, the battery recharging and replacement of nodes that have been exhausted are not possible. Sensor nodes in such wireless sensor network must be operated with a limited amount of battery to efficiently manage energy consumption. One of the most important issues in media access is energy consumption, which affects the lifetime of the nodes. Nodes can consume energy in the following ways [6,7]. Listening while idle: Especially in MAC protocols such as IEEE 802.11 and CDMA, a lot of idle listening is done, as they don't know whether a message will come or not, they remain listening all the time. The causes of waste of energy by the node mainly are.

i. Collision: When multiple nodes send their packets simultaneously to the receiver, these packets will be collided. Therefore, energy spent in resending damaged packages will be wasted.

ii. Latency: Depending on the application, the required delay time varies. Events should be forwarded to the sink node as soon as they are detected so that the necessary action can be taken in WSNs.

iii. Additional overheads: There will be a waste of energy for the header or control messages sent along with the data packets in WSNs.

Ultimately by minimizing the energy consumption of each node, lifetime of the network can be maximized. Energy-efficient MAC protocols were proposed such as S-MAC (Sensor-MAC) and Time-out MAC (T-MAC) which have reduced energy consumption to a considerable amount. Under constant traffic load T-MAC and S-MAC show the same performance. However, in a variable traffic situation, S-MAC efficiently saves more energy than T-MAC protocol. However, as the frequency of data generation increases, the chances of overhearing relatively increase, resulting in additional energy consumption and the transmission time, this may result in greater latency. In this research an energy efficient MAC protocol has been proposed to overcome the above shortcomings.

2. Related work

In Wireless Sensor Networks, the most important issue is energy conservation. Therefore, the main consideration in MAC design is energy efficiency. Other typical performance indicators such as fairness, throughput and delay are based on specific application systems which put forward different requirements. For different sensor network applications, various types of MAC protocols have been proposed. For example, large-scale wireless sensor networks, a competitive channel access method is adopted, while the scheduling mechanism for smaller-scale wireless sensor networks with high time requirements etc., different system requirements also focus on different MAC design. The MAC protocols of wireless sensor networks are mainly divided into four types:

i. MAC protocol based on synchronous contention. The contention-based MAC protocol uses the channel on demand. When a node needs to send data, the wireless channel is used in a competitive way. If the sent data conflicts, the data is retransmitted until the data is successfully sent or the data is discarded. In the synchronous MAC protocol, the node divides the time into several time frames, and each frame is divided into an active period and a sleep period. The node wakes up the radio frequency module during working hours to send and receive data, and shuts down the radio frequency module during sleep periods to save energy. A feature of this type of protocol is that all nodes are required to synchronize to a common time, so that all nodes in the network wake up at the same time to compete for the use of the channel. Generally speaking, synchronization and contention protocols require moderate global clock synchronization. Because the nodes work at the same time, the channel efficiency of this type of protocol is higher; but a disadvantage that follows is that contention and conflict are more serious. Synchronous contention-based protocols are developed from SMAC [8], and there are improved protocols such as TMAC [9], PMAC [10], and Sift [11].

ii. Based on asynchronous contention based MAC protocol. In the asynchronous MAC protocol, all nodes maintain their own independent work cycles, and when the nodes wake up, they immediately compete for the channel. In this type of protocol, because the receiving and sending parties are not synchronized, the receiving node may be in a sleep state when the sending node sends data, so a low power listening (LPL, also known as preamble sequence technology) method is required. To wake up the receiving node. Compared with the synchronous protocol, the asynchronous protocol does not need to maintain node synchronization, but requires additional wake-up energy consumption. The asynchronous contention based MAC mainly includes: BMAC [12], Wise MAC [13], XMAC[14], DFP. MAC [15], MFP. MAC [16], DPS. MAC [17].

iii. MAC protocol based on scheduling. The purpose of the scheduling protocol is to coordinate the work of each node in the network according to a set schedule. The schedule can be static pre-allocation or dynamic real-time allocation. According to the technical means used, scheduling protocols can be divided into protocols based on time division multiplexing (TDMA), code division multiplexing (CDMA), and frequency division multiplexing (FDMA) technologies. However, due to hardware constraints, scheduling protocols in wireless sensor networks mainly refer to TDMA-based protocols. The idea of TDMA is to interleave different signals in different time periods and transmit them along the same channel. The TDMA mechanism in the wireless sensor network is to allocate an independent time slot for each node to send information, and the node goes to sleep in other time slots. The TDMA mechanism has no competing collision retransmission problems, and data transmission does not require too much control information. These features meet the energy-saving requirements of MAC for wireless sensor networks. However, the TDMA mechanism requires strict time synchronization between nodes, and the TDMA mechanism has insufficient network scalability: Typical MAC based on TDMA mechanism includes TRAMA [18], LMAC [19], DMAC, AI-MAC, LEACH and other protocols.

iv. Hybrid type MAC protocol. Sometimes in order to save energy and ensure the scalability of the system, a hybrid MAC mechanism combining the contention mechanism CSMA and time division multiplexing TDMA is adopted. A typical MAC protocol based on joint design is IEEE 802.15.4, ZMAC, SCPMAC, Funnelin MAC, THMAC protocol.

In recent years, scholars from various countries have focused on energy-efficient data transmission protocols in sensor networks, lot of research has been done on MAC layer, routing layer to transport layer. The optimization and improvement of the transport layer have effectively reduced the network packet loss rate and energy consumption also enhances the reliability of the network.

This section focuses on the analysis of the MAC layer solutions to develop energy efficient MAC from existing protocol by using buffering technique. SMAC (Sensor- MAC) is the first completely designed for sensor networks based on the MAC protocol of IEEE802.11, its important contribution is the introduction of node sleep mechanism. The node sleeps periodically taking the neighbouring node's sleep scheduling into consideration. TMAC is an improvement on the basis of SMAC. The node sleep schedule strategy has been adjusted appropriately, according to the network; the sleep time of nodes is dynamically adjusted to improve protocol efficiency for example in B-MAC, Wise MAC, X-MAC, and Z-MAC [20] protocols. In this section, we discuss and briefly review the existing MAC protocols such as S-MAC and T-MAC and also analyse the problems.

S-MAC is a regional synchronization based high-energy efficient than 802.11 MAC protocol. In the S-MAC protocol time is divided into several frames, the frame length is determined by the application, and the frame is divided into two parts: activity and sleep. During the sleep period, the node closes the transmitter module, and the buffer is responsible for collecting data information at this time. The data is in the waiting sequence and sent in the active phase. At the beginning of the activity, the sending node enters the synchronization mechanism to determine the length of the frame, and then sends data information through the (RTS/CTS/DATA/ACK) mechanism. This mechanism can avoid energy consumption due to collisions. Through the synchronization mechanism, the same time period and the same wake-sleep strategy can be adopted between local nodes, which facilitate the wireless sensor network to discover new nodes.

To reduce the energy consumption of WSN nodes in wireless sensor networks, S-MAC protocol was proposed based on IEEE 802.11. The wireless sensor network loses most of the energy due to conflicts in retransmissions, control signal overheads, idle listening, overhearing, etc., S-MAC introduces a SYNC mechanism between nodes, allowing nodes to enter sleep mode if they do not have any data to send and receive. But as discussed above, sleep itself will cause the data transmission to be interrupted, thereby increasing the delay. The following will specifically analyse how the S-MAC protocol saves energy. Alternate listen/sleep mechanism: The working of the S-MAC protocol is carried out according to the duty cycle. All the

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nodes in the S-MAC protocol will work for a period of time and sleep for a period of time, in each cycle. Energy will be saved by reducing the working time of nodes. As shown in Fig. 2, one cycle of the S-MAC protocol includes two phases: sleep and wake up. The wakeup phase belongs to the working phase. If a data packet is received in the wake-up phase, communication will be established between nodes. If the node is in a sleep state, the node cannot receive any data, and the data sent to it will be blocked. A node in a sleep state will wake up after a certain period of time. In the S-MAC protocol, adjacent nodes sleep and wake up at the same time as much as possible. To ensure time consistency and prevent clock drift, different nodes need to periodically broadcast synchronization packets to exchange time information, so as to adjust and synchronize.

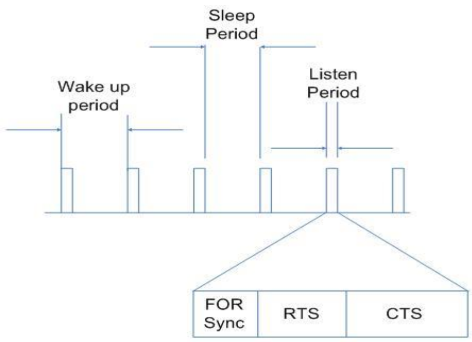

Fig. 2. S-MAC principle [4].

S-MAC protocol uses a "virtual cluster" mechanism. Under the "virtual cluster" mechanism, the scheduling information between nodes is sent by the nodes broadcasting SYNC packets. The S-MAC protocol uses a scheduling table to store scheduling information, and each node keeps a scheduling table. The node will monitor for a period of time at the beginning of start-up, because the S-MAC protocol has a fixed duty cycle, so this period is fixed. During the monitoring period, if the node receives the scheduling information of the neighbouring node, it uses the neighbouring node schedule to update its schedule, and it will broadcast its schedule after a while. If the received neighbour node's schedule is same as its schedule, then its schedule will not change; if the neighbour node's schedule is found to be different from its own, the new schedule will be used.

When there is a transmission of large amount of data during the fixed active time, by using S-MAC it is a waste of energy due to the fixed duty cycle. It can be said that the S-MAC protocol is considered quite comprehensive, but it still has its own shortcomings. First, the synchronization in the periodic sleep monitoring brings a certain control packet overhead, the synchronization and maintenance will consume the node resources. In addition, the sleep cycle is restricted by various aspects, and cannot meet the requirements of ultra-low power consumption as the cycle length is limited by the delay requirement and the cache size, the cycle length directly reflects the energy-saving. Secondly, in the large-scale sensing network, periodic sleep cycle will bring an unbearable delay problem (adaptive traffic monitoring cannot be effectively solved). Finally, the energy consumption of end nodes is much larger than that of ordinary nodes, resulting in unbalanced energy consumption between nodes. T-MAC was proposed to solve the problem of not being able to transmit data in fixed duty cycle.

In T-MAC, the active nodes will conserve energy by going into sleep state, if there is no data to transmit during the wakeup operation time, until the start of the next duty cycle. Simultaneously transmit data during the active time, if there is no transmission/reception of data, a timer is operated for a certain amount of time, enables sleep mode in T-MAC. Figure 3 shows the T-MAC using synchronous timer, if there is no data to transmit or receive node goes to sleep after a fixed time T_n.

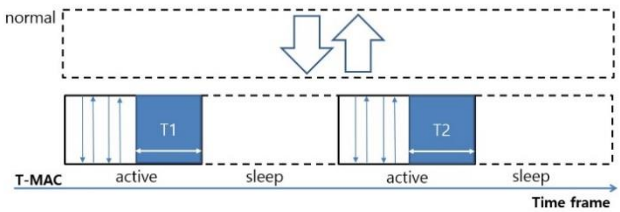

Fig. 3. T-MAC Protocol operation. [*].

Therefore, it saves energy by reducing unnecessary idle listening, improves efficiency; However, S-MAC increases the frequency of data transmission. As in case of S-MAC, the overhearing rate is relatively high, and hence energy consumption is more. In addition, the timer is synchronized regardless of the duty cycle. Data transmission delay may occur by using the technique of transmitting sync signal with the data.

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3. Adaptive Buffer threshold-MAC (AB-MAC)

AB-MAC sets a differential threshold in each node's buffer, the buffer threshold varies depending on the number of hops between each node and sink. When the data stored in the node exceeds the threshold value, the node transmits the data. In the proposed technique, the timer is similar to T-MAC, and the node sets a timer while working RTS, CTS (Clear-to-Send), FRTS (Future RTS). If a data packet is received or no data packet is sent, the node enters sleep mode.

The efficiency of existing protocols decreases when the amount of traffic is varied. AB-MAC protocol optimizes energy efficiency using dynamic thresholds in buffers based on the number of hops between nodes and sink. As given in Fig. 4 it shows the concept of AB-MAC structure.

The operation of AB-MAC is that the data sensed during sleep mode is stored in the buffer. When the amount of accumulated and sensed data in active mode crosses the threshold value, the data will be transmitted. When a node creates a data packet, the packet header will record detection time, node ID, and grade of context.

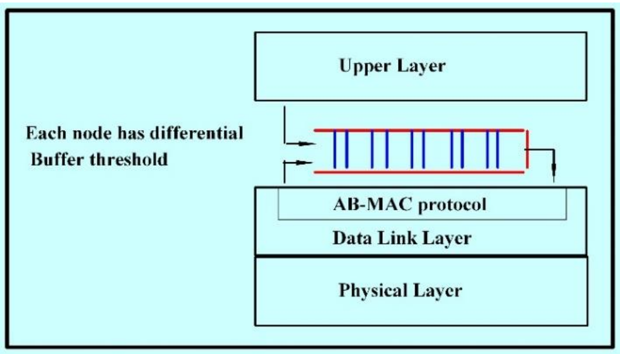

Fig. 4. Proposed Protocol Structure.

3.1 Buffer Threshold Settings

The buffer threshold setting is given as a differential value to each node based on the number of hops, and data is transmitted when the sensed data exceeds the specified threshold limit. Since all nodes have different thresholds, the node that received data exceeds the buffer threshold, immediately transmits data to the next node. The packet header will record detection time, node ID, and grade of context.

Table 1. Parameters used to determine the threshold

Parameter	Value
Q_{TH}	Buffer Threshold
Q_T	Total size of the buffer
Q_A	Amount of data accumulated in the buffer

Therefore, the proposed AB-MAC is energy efficient in a multi-hop network. To extend network lifespan, the following energy conservation technique is used; the threshold value of buffers of each node is set differentially according to the number of hops from the sink node. Fig. 5 shows that each node determines the buffer threshold by the number of hops from the sink node. Node-D's buffer exceeds the threshold value while sending a packet to node-C. The threshold value of node-C is larger than Node-D, which increases the probability of going to sleep. This approach improves the energy efficiency of each node.

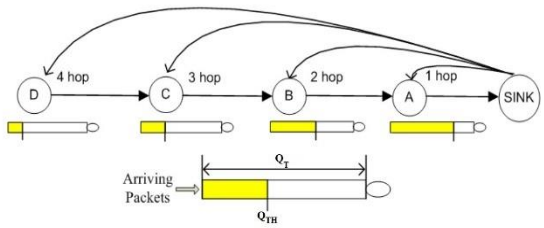

Fig. 5. Buffer threshold setting based on the hop-count from the sink.

To determine the node's threshold value, α and λ are used as parameters. α is a parameter that reflects the hop count and λ is the rate of change of the threshold value. α is difference in the number of hops of the source node (N_{total}) and the number of hops of the sink node (N_{own}).

If α is equal to or greater than the difference of hops, the threshold value Q_{TH} is determined by equation (1),

□□□ = □□ x { λ^(□−(□□□□□ − □□□□)) }, □ > (□□□□□ − □□□□)--(1)

Where □□ is the total size of the buffer, and 0 ≤ □□□<1.

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If α is less than the difference or when the two hops are same (i.e. the origin node), the threshold value is as given in the equation (2).

□□□ = □□x λ, $\alpha <$ (□□□□□□ − □□□□) or □□□□□□ − □□□□ = 0 ---- (2)

3.2 Priority data transfer

In addition to the differential buffer threshold policy of each node, set according to the number of hops with the sink, AB-MAC also uses a transmission method according to the importance of data using the data priority. In the AB-MAC to improve energy efficiency, data is collected and transmitted when the threshold is exceeded, it may result in performance deterioration in terms of transmission delay.

Frame Control	Duration	Data Priority	Receiver Address	Transmitter Address	FCS

Fig. 6. RTS frame structure of AB-MAC protocol.

Therefore, to actively cope with data transmission delays, data types and priorities are classified to ensure fast transmission of urgent data. Fig. 6 shows priority field is included in the frame structure of the proposed protocol. The node receives the RTS message with data priority. If the message requires urgency, by checking the field value transmission is attempted regardless of the amount of data in the current buffer or the threshold value.

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4. Results and Analysis

In order to verify the effectiveness and feasibility of this algorithm, a simulation experiment was performed on the MATLAB 2010a platform. In the experiment, it is assumed that 200 nodes are randomly distributed in an area of 100 m × 100 m in area. The initial energy of each node is randomly obtained in the energy interval [1 J, 1.5 J], and the sink node is located in the centre of the area. The content of the experiment is to compare the AB-MAC algorithm with the protocols S-MAC and T-MAC algorithms in. The efficiency of the AB-MAC algorithm is evaluated based on the following criteria: throughput, energy consumption, average delay and packet delivery ratio. The experimental results are the average results after running 10 times.

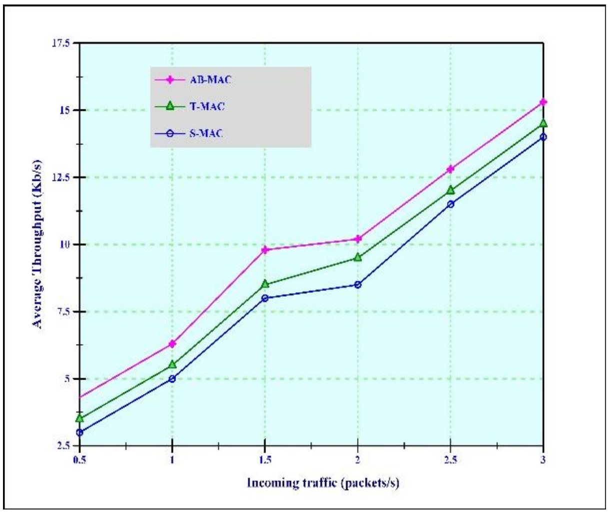

Fig. 7. Throughput analysis with varying incoming traffic.

In the Fig. 7 represents the throughput analysis of proposed and the existing protocols by varying incoming traffic. It can be noticed, improvement in the throughput by proposed algorithm.

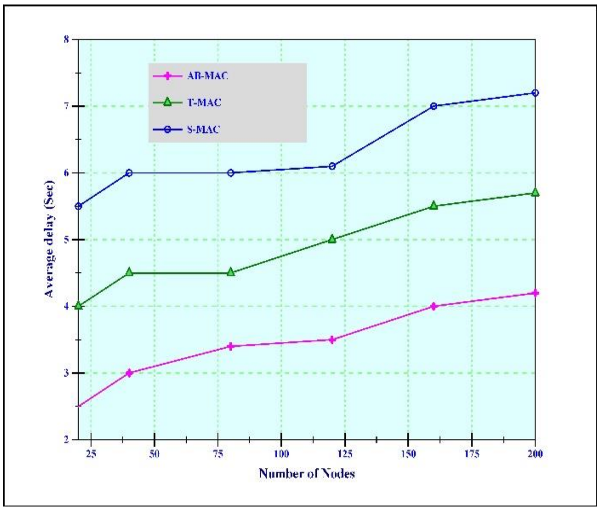

Fig. 8 Average delay by varying number of nodes in the network.

Average delay between the AB-MAC with S-MAC and T-MAC protocols (Fig. 8). It shows the proposed protocol takes lesser time to transmit the data to sink node.

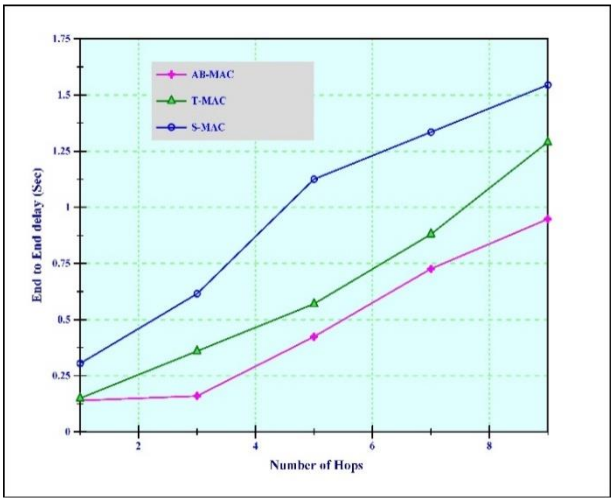

Fig. 9 Latency by varying number of hops from the sink.

Fig. 9 shows the End to End delay comparison with the number of hops, the proposed protocol takes a lesser amount of time for transmission when compared to existing protocols.

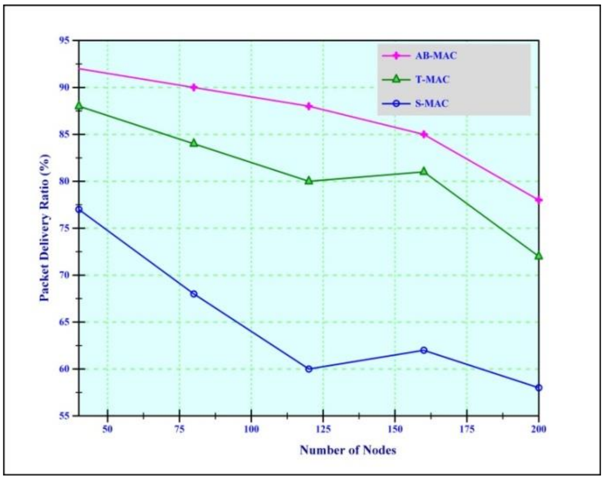

Fig. 10 Analysis of Packet Delivery Ratio by varying number of nodes.

Packet Delivery Ratio (Fig. 10) of the proposed AB-MAC with the existing T-MAC and S-MAC protocols. The proposed protocol performs better, results in a greater packet delivery ratio than the existing protocols.

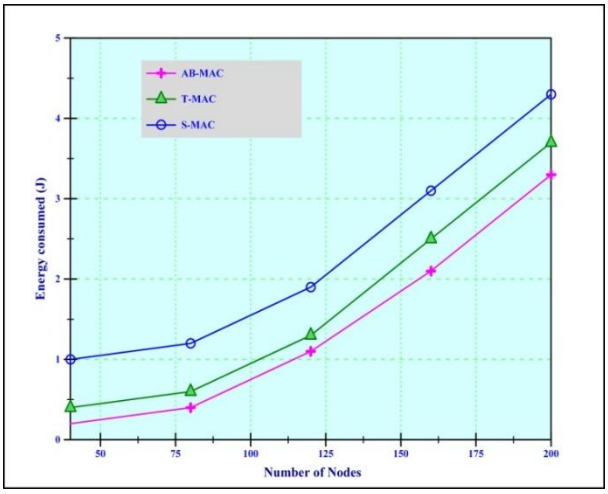

Fig. 11 Analysis of Energy consumption by varying number of nodes.

Energy efficiency analysis (Fig. 11), energy consumed between AB-MAC with S-MAC and T-MAC protocols by a varying number of nodes, as the figure shows proposed protocol is energy efficient.

5. Conclusion

In this paper, an adaptive buffer threshold-based MAC protocol (AB-MAC) has been proposed, to improve energy efficiency and data latency of Wireless Sensor Networks. A simulation was conducted using MATLAB 2010a. Four performance indicators have been chosen to evaluate the performance of the proposed protocol, Throughput, End-to-end delay, Average energy, and Packet delivery ratio. Simulation results show that the proposed protocol AB-MAC can effectively save energy while maintaining low perceived latency when compared with the S-MAC and T-MAC in the dense network environment.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Sudhakar Chekuri developed the concept, performed the numerical analysis, simulation, and prepared initial manuscript. B. N. Bhandari verified the method, supervised the findings of this works, evaluated and edited the manuscript draft. All authors discussed the results and contributed to the final manuscript.

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