H-MAC: A Hybrid Medium Access Control Protocol for Wireless Sensor Networks

Bamuli Swapna[1], S.Srujana[2]
[1,2] *Assistant Professor Vaagdevi Degree & PG College, Hanamkonda, Telangana-506001*

Abstract: In this paper, we introduce H-MAC, a hybrid medium access control protocol for wireless sensor networks. H-MAC combines the power-saving mechanism (PSM) from IEEE 802.11 with slotted Aloha, dynamically utilizing multiple slots to enhance performance. While existing MAC protocols for sensor networks reduce energy consumption through active/sleep cycle variations, they often fail to maintain energy efficiency under varying traffic conditions and do not address Quality of Service (QoS) issues. H-MAC, on the other hand, ensures both energy efficiency and QoS aspects such as latency, throughput, and channel utilization. Our numerical results demonstrate that H-MAC significantly improves QoS parameters compared to existing MAC protocols for sensor networks, while consuming a comparable amount of energy.

***Keywords:* Sensor networks, Medium Access Control (MAC) protocol, energy optimization.**

1. INTRODUCTION

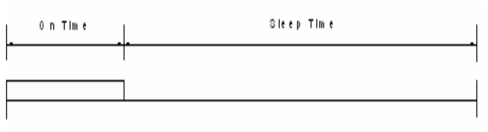
Wireless sensor networking is an emerging technology with diverse applications, such as monitoring, medical systems, and robotic exploration. These networks typically consist of a large number of densely deployed, distributed nodes that self-organize into multi-hop wireless networks. The sensor nodes are often powered by limited energy sources, and in some cases, replacing the power source may not be feasible. As a result, researchers are focusing on designing power-aware protocols and schemes for sensor networks. These include power-saving hardware designs, efficient topology configurations, and energy-efficient MAC layer protocols, among others. Communication in wireless sensor networks is organized into several layers, one of which is the Medium Access Control (MAC) layer. The MAC layer is crucial for ensuring the successful operation of the network, as it helps avoid collisions between nodes, ensuring that interfering nodes do not transmit at the same time. Various MAC protocols have been developed for wireless sensor networks, with examples including S-MAC and T-MAC. These protocols are typically designed to optimize throughput and Quality of Service (QoS), but in wireless sensor networks, MAC protocols prioritize minimizing energy consumption over QoS. Traditional MAC protocols can waste energy due to idle listening, collisions, protocol overhead, and overhearing-MAC was proposed to enhance energy efficiency in wireless sensor networks by dividing time into large frames, each consisting of an active part (on-time) and a sleeping part. During sleep time, a node turns off its radio to conserve energy, while during active time, it communicates with neighbors and transmits queued packets. This mechanism reduces energy waste from idle listening but can lead to high latency and low throughput, particularly in multi-hop sensor networks. To improve S-MAC under variable traffic conditions, the Timeout-MAC protocol was introduced. It uses a minimum timeout timer, TA, to end active time when no activation occurs for a specified period. While it improves energy efficiency, T-MAC can result in early sleeping and low throughput. The Data Gathering MAC (D-MAC) protocol, a duty cycle-based MAC, focuses on low latency and energy efficiency. It is an enhanced slotted Aloha protocol where slots are assigned based on a data gathering tree structure (parent-child topology). D-MAC reduces latency by assigning subsequent slots to nodes in the data transmission path but works best for tree-based structures and may cause collisions. Pattern-MAC is a time-slotted protocol that adapts the sleep-wake schedule of nodes based on their own traffic and that of their neighbors. It allows nodes to enter long sleep periods when there is no network activity and wake up when necessary. This approach saves more energy than S-MAC without sacrificing throughput, but it can introduce complexity, collision, and overhead issues. To maximize battery life, MAC protocols for sensor networks typically use a variation of the active/sleep mechanism, which trades QoS for energy savings. However, the proposed H-MAC not only reduces energy consumption but also provides good QoS in terms of latency, throughput, and channel utilization. Comparing the previous work in various protocols are evaluated based on different factors, as summarized in Table 1.

Table 1. Comparison table

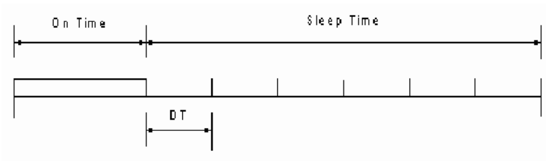
Protocol	S-MAC	T-MAC	D-MAC	P-MAC	H-MAC
Time-Sync.	Yes	Yes	Yes	Yes	Yes
Point to Point	Suitable	Suitable	Not-Suitable	Suitable	Suitable
Broadcast	Not-Suitable	Not-Suitable	Not-Suitable	Suitable	Suitable
Convergecast	Not-Suitable	Not-Suitable	Suitable	Suitable	Suitable
Mobility	Not-Suitable	Not-Suitable	Not-Suitable	May be	May Be
Type	CSMA	CSMA	TDMA/S. Aloha	Slotted Aloha	CSMA/S. Aloha
Adaptive to change	Ok	Good	Weak	Good	Good
Half/Full Duplex	Half	Half	Full	Full	Full

2. H-MAC PROTOCOL

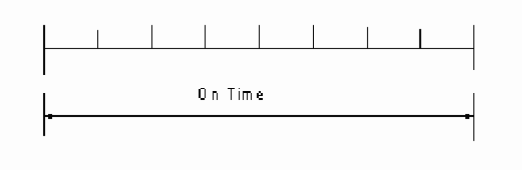
We present a new hybrid MAC protocol- H-MAC, for sensor networks. H-MAC is based on IEEE 802.11's PSM mode and slotted aloha [6]. In H-MAC, time is divided into large frames, every frame has two parts: an active part (on time) and a sleeping part. Active part is like ATIMwindow in PSM mode and sleeping part is further divided into N slots, where each slot is bit bigger than data frame. Figure 1 shows the comparison between S-MAC and H-MACtime frames.



(a) A time frame of S-MAC protocol



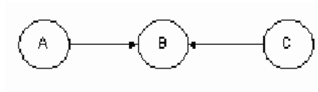
(b) A time frame of H-MAC protocol



(c) On time frame of H-MAC protocol

Figure 1. Time frame of S-MAC and H-MAC protocols

The nodes that have packets to transmit negotiate slots with the destination nodes during activetime and transmit/receive the data packets in pre-negotiated slots during sleep time. If the nodesdon't have to transmit or receive any data packets go to sleep during the sleep-time slots. Figure2 illustrates the working of H-MAC.



(a) An example topology

If node A has buffered packets destined for node B, it will notify node B by sending ATIM packet. Node A includes its preferable slot(s) list in the ATIM packet. Node B, upon receiving the ATIM packet, select slot(s) based on sender's list and its own list. The receiver's list has higher priority in selecting the slot(s). After Node B selects a slot(s), it includes the slot information in the ATIM-ACK packet and sends it to node A. When node A receives the ATIM-ACK packet, it sees if it can also select the slot(s) specified in the ATIM-ACK. If node A selects the slot(s) specified in the ATIM-ACK, node A sends an ATIM-RES (ATIM- Reservation) packet to the node B, with node A's selected slot(s) specified in the packet. The ATIM-RES is a new type of packet used in our MAC scheme, which is not in IEEE 802.11 PSM. The ATIM-RES packet notifies the nodes in the vicinity of node A which slot(s) node A is going to use, so that the neighbouring nodes can use this information to update their list. Similarly, the ATIM-ACK packet notifies the nodes in the vicinity of node B. After the ATIM (On time) time, node A and node B will transfer the data packet(s) in selected slot(s).

3. NUMERICAL RESULTS

In this section, we show latency and throughput analysis of S-MAC and H-MAC protocols. As S-MAC is widely accepted and popular sensor networks MAC protocol, we choose S-MAC for comparison with H-MAC For our calculation we consider 10 hops liner topology as shown in figure 3.

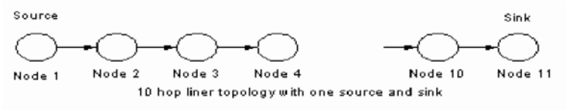


Figure 3. 10 hops liner topology

And we also consider 20 slots per cycle, where 18 slots are used for data transfer and 2 slots for handshaking signals.
The entire latency over N hops is given by

$$D(N) = \sum_{n=1}^{N} (t_{cs,n} + t_{tx}). \qquad (1)$$

Where, N is the number of hops. $t_{cs,n}$ and t_{tx} represents backoff and transmission delay respectively. And *n* represents the current hop value, average latency over N hops is given by

$$E[D(N)] = N(t_{cs,n} + t_{tx}) \qquad (2)$$

S-MAC Protocol:
In S-MAC, a complete cycle is denoted by T_f and has two parts: an active part and a sleep part.

Listen/active time is fixed and set to 10% of T_f (10% duty cycle). The delay at hop n is given by

$$D_n = t_{s,n} + t_{cs,n} + t_{tx} \qquad (3)$$

Where, $T_f >> t_{tx}$ and $t_{s,n}$ is the sleep delay. In S-MAC without adaptive listening, contention only starts at the beginning of each frame. This is given by

$$T_f = t_{cs,n-1} + t_{tx} + t_{s,n} \qquad (4)$$

So the sleep delay at hop n is given by

$$t_{s,n} = T_f - (t_{cs,n-1} + t_{tx}). \qquad (5)$$

Substituting (5) in to (3)

$$D_n = T_f + t_{cs,n} - t_{cs,n-1} \qquad (6)$$

A packet can be generated on the source node at any time within a frame, so the sleep delay on the first hop,
$t_{s,1}$, is a random variable whose value lies in (0, T_f). Suppose $t_{s,1}$ is uniformly distributed in (0, T_f). Its mean value is T_f 2 . Combining it with (6), the overall delay of a packet over N hops is given by

$$\begin{aligned} D(N) &= D_1 + \sum_{n=2}^{N} D_n \\ &= t_{s,1} + t_{cs,1} + t_{tx} + \sum_{n=2}^{N} \left(T_f + t_{cs,n} - t_{cs,n-1}\right) \qquad (7) \\ &= t_{s,1} + (N-1)T_f + t_{cs,N} + t_{tx} \end{aligned}$$

The average latency of S-MAC without adaptive listen over N hops is given by

$$\begin{aligned} E[D(N)] &= E[t_{s,1} + (N-1)T_f + T_{cs,N} + t_{tx}] \\ &= T_f/2 + (N-1)T_f + t_{cs} + t_{tx} \qquad (8) \\ &= NT_f - T_f/2 + t_{cs} + t_{tx}. \end{aligned}$$

From the (8) we can observe that the multihop latency linearly increases with the number of hops in S-MAC when each node strictly follows its sleep schedule(s).

H-MAC Protocol:
H-MAC is similar to S-MAC with only one difference of slotted sleep time.

In H-MAC, time frame T_{f-X} is given by

$$T_{f-x} = t_{active} + Ct_{s,n} \qquad (9)$$

Where C is the number of equal length slots and t_{active} is the listen time same as S-MAC (10% duty cycle). During the t_{active} time H-MAC can reserve the slots for n_r hops within the same T_{f-x}, so the delay for 1 hop transmission over n_r hops is given by

$$D_1 \approx T_{f-x}/n_r \qquad (10)$$

From the (10), we can also calculate the delay for N hops as

$$D(N) \approx \sum_{n=1}^{N} D_1 \qquad (11)$$

From (10) and (11), we can calculate the average latency of H-MAC as

$$\begin{aligned} E[D(N)] &\approx E[\sum_{n=1}^{N} D_1] \\ &\approx N(T_{f-x}/n_r) \qquad (12) \\ &\approx \lceil N(T_{f-x}/n_r) \rceil \end{aligned}$$

Where ⌈*⌉ define the largest integer value which is equal to *. From (12) we can observe that the multihop latency linearly increases with the number of hops in

H-MAC as in S-MAC. However, the slop of the line changes to T_{f-x}/n_r.

Throughput Analysis:

Here, packet length is fixed and represented by t_p. Sleep time is represented by t_{Sleep}

And equivalent to Ct_s. Actual data transmission take place only during the sleep time and $t_{Sleep} >> t_p$.

Hence, the throughput is given by

$$Th = \frac{t_{sleep}}{t_{active} + t_{sleep}} \qquad (13)$$

S-MAC Protocol:

In S-MAC, a node can communicate n_p the packets to only one node nodes within a frame time. So the throughput is given by

$$Th_s = \frac{n_p}{t_{active} + t_{sleep}} \qquad (14)$$

H-MAC Protocol:

In H-MAC, a node can communicate n_p packets to maximum n_m nodes within a frame time. So the throughput is given by

$$Th_x = \frac{Ct_s}{t_{active} + Ct_s} = \frac{n_p n_m}{t_{active} + Ct_s} \qquad (15)$$

from (14) and (15) it is clear that H-MAC gives better throughput condition compared to S- MAC.

Now we present analysis to find the ratio of successful transmitted messages[3] [9]. Here, active time is fixed and equivalent to S_m slots. There are N nodes to compete for medium/slots. A node can transmit only one request.

Let n be the number of nodes tries to get the same mini-slot among N nodes. The request messages are uniformly distributed in an active time. The probability that n nodes are in a slot is given by binomial distribution as follows

$$P[X = n] = \binom{N}{n}\left(\frac{1}{S_m}\right)^n \left(1-\frac{1}{S_m}\right)^{N-n} \qquad (16)$$

The above binomial distribution also applies to S_m slots, thus the expected value of the number of slots with n nodes in a slot is given by

$$E[X = n] = S_m \binom{N}{n}\left(\frac{1}{S_m}\right)^n \left(1-\frac{1}{S_m}\right)^{N-n} \qquad (17)$$

C_n represents the number of slots being filled with exactly n nodes. So the average number of collided messages is given by

$$\sigma = \sum_{n=2}^{N}\sum_{c_n=1}^{S_m} nP[X = C_n]C_n = \sum_{n=2}^{N} nE[X = C_n] = \sum_{n=2}^{N} nS_m \binom{N}{n}\left(\frac{1}{S_m}\right)^n \left(1-\frac{1}{S_m}\right)^{N-n} = N - N\left(1-\frac{1}{S_m}\right)^{N-1} \qquad (18)$$

from (17) and (18) we can calculate the ratio of the number of successfully transmitted request messages and the total number of transmitted request messages. The ratio is given by

$$Ratio = \frac{N-\sigma}{N} = \left(1-\frac{1}{S_m}\right)^{N-1} \qquad (19)$$

Figure 4 shows the throughput of the network while varying the number of packets transmitted from sink to source. After 8 packets H-MAC's throughput reduces to S-MAC throughput, as H- MAC can't transmit the packets simultaneously above 8 packets and data packets take more cycles to reach sink[4]. Figure 5 shows the energy consumption of the network, S-MAC and H- MAC consumes the same amount energy. Figure 6 shows the latency performance of S-MAC and H-MAC. H-MAC performs notably well compared to S-MAC, as it can transmit the data simultaneously to other nodes. Figure 7 and 8 shows the ratio of successful transmitted message. First result we obtain by varying the number of neighbouring nodes, and keeping cycle size of 20 slots. Similarly, second result we obtain by varying the number of slots in given cycle, and keeping the neighbouring nodes constant.

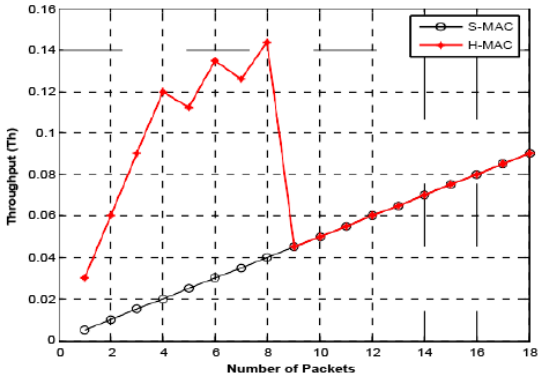


Figure 4. Throughput of the network

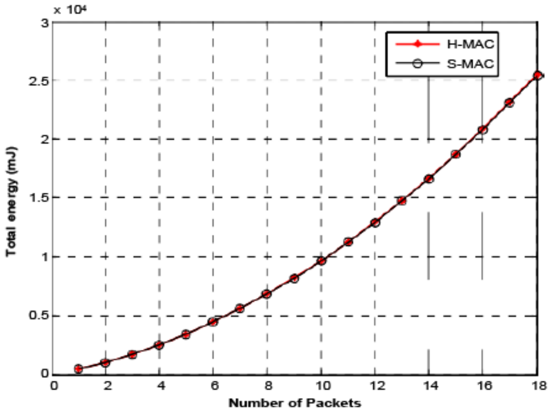


Figure 5. Total energy consumption

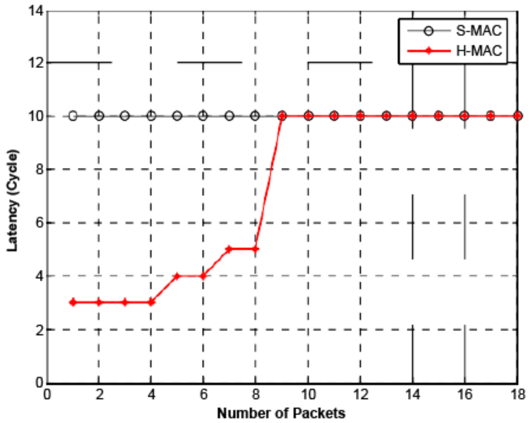


Figure 6. Latency performance

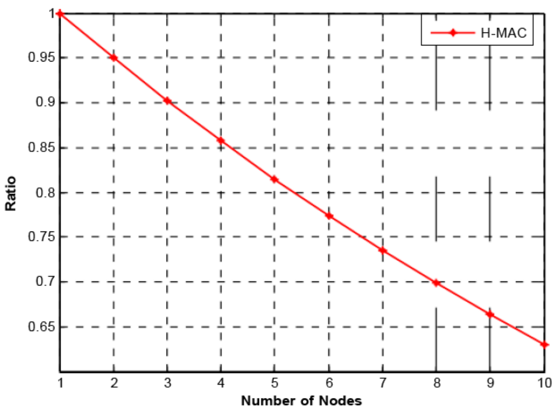


Figure 7. Ratio of successful transmitted messages

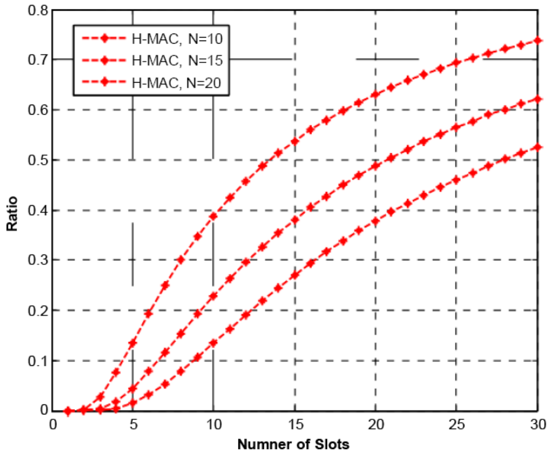


Figure 8. Ratio of successful transmitted messages

4. CONCLUSIONS

In this paper, we introduce the H-MAC protocol, a hybrid MAC protocol that combines IEEE 802.11's PSM mode with slotted Aloha, dynamically utilizing multiple slots to enhance performance. We also provide numerical results for H-MAC, demonstrating that it significantly improves QoS parameters compared to existing MAC protocols for sensor networks, while consuming a comparable amount of energy.

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