A Hybrid MAC with Dynamic Sleep Scheduling for Wireless Sensor Networks

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<Summary> In this paper, we present Hybrid MAC (H-MAC), a novel low power with minimal packet delay medium access control protocol for wireless sensor networks (WSNs). H-MAC achieves high energy efficiency under wide range of traffic load. It ensures high channel utilization during high traffic load without compromising energy efficiency. H-MAC does it by using the strength of CSMA and TDMA approach with intelligence. The novel idea behind the H-MAC is that, it uses both the broadcast scheduling and link scheduling. Depending on the network loads the H-MAC protocol dynamically switches from broadcast scheduling to link scheduling and vice-versa in order to achieve better efficiency. Furthermore, H-MAC uses Request-To-Send (RTS), Clear-To-send (CTS) handshakes with methods for adapting the transmit power to the minimum level necessary to reach the intended neighbor with a given BER target or packet loss probability. Thus H-MAC reduces energy consumption by suitably varying the transmit power. The simulation results corroborate the theoretical idea, and show the efficiency of our proposed protocol.

Keywords: hybrid MAC, dynamic sleep scheduling, wireless sensor network, energy consumption, CSMA, TDMA

1. Introduction

Wireless sensor networks (WSNs) have become very popular in recent years. Many WSNs are based on proprietary standards for wireless networking, but the recent trend has been increasingly towards the standardization of low power wireless communication. The first step of standardization for such low rate wireless personal area networks was taken in 2003 when IEEE 802.15.4 was approved. IEEE 802.15.4 standard specifies only the lowest part of OSI communication model: PHY layer and MAC sub-layer which are briefly overviewed with the area of our proposed work in Fig. 1. With 802.15.4, IEEE had a goal in mind for low-cost, low-power

and short-range wireless communications. This standardization process continued and went through an enhancement process. As a result, newer versions like IEEE 802.15.4b, 802.15.4a, 802.15.4c and 802.15.4d were released subsequently. But unlike 802.11 WLAN cards where MAC is usually included as part of the chipset, in WSNs the MAC designer has absolute control on the design of MAC layer. So, on the basis of IEEE 802.15.4 standard though a lot of MAC protocols for sensor networks have been proposed in recent years, still researchers are settled and agreed on one point that a definite and universally accepted standard MAC protocol for wireless sensor network is really needed. We hope our H-MAC protocol will certainly contribute to the standardization process of MAC layer protocol for wireless sensor network.

WSN consists of a large number of wireless sensor nodes that are deployed randomly. The sensor nodes are typically small, and equipped with low-powered battery. Unlike other wireless networks, it is generally impractical to charge or replace the exhausted battery. Since prolonging lifetime of the sensor nodes is very important, energy efficiency becomes the most important attribute of design of MAC protocol of sensor networks. Other attributes are fairness, latency, delivery ratio, and bandwidth1). Idle listening is the major source of energy wastage for wireless sensor networks2). Therefore, in sensor network, nodes do not wake-up all the time rather prefer energy preservation by going to sleep time to time as explained in Fig. 2.

After the sleep scheduling, nodes could operate in a low duty cycle which can significantly save energy and extend the network lifetime at the expense of increased communication latency and synchronization overhead. In reference 3), different sleep

Fig. 1. Structure of IEEE 802.15.4 protocol stack and the area of our proposed work
scheduling schemes are analyzed and a scheduling methods that can
decrease the end to end delay is proposed. But this method
does not provide an interference free scheduling. One obvious
approach is TDMA MAC which can inherently support low duty
cycle operation. Besides TDMA has natural advantage of
contention and collisions free transmission\(^1\). To be interference
free, a straightforward approach can be to assign each
communication link a slot, and thus the number of slot is equal to
the number of communication links of the network. However, this
scheme requires much more slots than necessary, which enhance
delay and reduces the channel utilization. Moreover, minimizing
the number of slot assignment for producing an interference free
link scheduling is a NP complete problem\(^4\). On the other hand
performance of broadcast scheduling is worse than link scheduling
in WSNs, in terms of energy conservation. Henceforth, we propose
a new hybrid MAC protocol for wireless sensor network, called
H-MAC, which combines the strength of CSMA, link scheduling
and broadcast scheduling.

The rest of the paper is organized as follows. Section 2 reviews
related works. In Section 3 we will elaborate on the design of the
H-MAC protocol. In section 4 we will describe an analytical
model, followed by results in section 5. And finally section 6
concludes the paper and mentions some guideline of the scope of
future works.

2. Related Work

For sensor network, S-MAC\(^2\) is one of the pioneering works in
contention based MAC protocol. In S-MAC nodes operates in low
duty cycle and energy efficiency is achieved by periodic sleeping.
Nodes form virtual clusters, based on common sleep schedules, to
reduce control overhead and enable traffic adaptive wake-up.
T-MAC\(^3\) improves the energy efficiency of S-MAC by introducing
adaptive duty cycle. T-MAC reduces the idle listening by
transmitting all messages in burst of variable length and sleeping
between bursts and it maintains an optimal active time under
variable load by dynamically determining its length.

TDMA has long been dismissed as an unfeasible solution for
wireless ad hoc networks for its lack of scalability and adaptability
to varying environments. However, it provides a good energy
efficient and collision free communication. Recently several
technique\(^6, 7\) have been proposed for TDMA in sensor networks.
Nevertheless, these protocols still are unsuccessful to address the
fundamental difficulties that stand-alone TDMA scheme face.

In our previous work\(^8\) we first introduce the novel idea of
combining broadcast scheduling (broadcast TDMA) and link
scheduling (pair wise TDMA) together in order to gain energy
efficiency as well as efficient use of bandwidth.

In AMAC\(^9\) each node can adjust duration of the active period
depending on traffic. In reference 10), the performance analysis of
optimized medium access control for wireless sensor network is
done. B-MAC\(^11\) is the default MAC for Mica2. B-MAC allows an
application to implement its own MAC through a well-defined
interface. They also adopt LPL (Low power listening) and engineer
the clear channel sensing (CCA) technique to improve channel
utilization. Z-MAC\(^12\) dynamically adjusts the behavior of MAC
between CSMA and TDMA depending on the level of contention
in the network. The protocol uses the knowledge of topology and
loosely synchronized clocks as hints to improve MAC performance
under high contention. Z-MAC uses DRAND\(^13\), a distributed
implementation of RAND\(^14\) to assign slot to every node in the
network. TH-MAC\(^15\) is a traffic pattern aware hybrid MAC
protocol inspired from Z-MAC. It uses A-DRAND as slot
assignment algorithm. A-DRAND is an improved version of
DRAND for clustered wireless sensor networks where cluster
heads require more slots to relay packets. BAZ-MAC\(^16\) is another
hybrid MAC protocol inspired from Z-MAC and proposed for Ad
Hoc networks. Like TH-MAC, BAZ-MAC uses a bandwidth aware
slot allocation algorithm during the set-up phase, to assign slots to
the nodes according to their bandwidth requirements. In PH-
MAC\(^17\), authors use contention period to allocate the timeslot to
every node that needs to transmit data, and the TDMA part to
transmit actual data.

Our proposed H-MAC also combines TDMA and CSMA. But
H-MAC is completely different from Z-MAC and similar hybrid
MAC in the sense that in H-MAC, each node calculates its own
slot independently which is very flexible. Moreover, the hybrid
concept used in case of H-MAC does not stand for the same
meaning, as the meaning used by other already proposed hybrid
MAC. H-MAC is hybrid in the sense that it combines CSMA, the
broadcast scheduling and link scheduling dynamically to improve
the energy efficiency. Another important feature of H-MAC is that
it reduces energy consumption by suitably varying the transmit
power.

3. Hybrid MAC (H-MAC) Protocol Design

We first define the terminology used in this paper. A Slot or
Frame is defined as the periodic interval, which consists of an
active period and a sleep period. A duty cycle is the proportion of
active period to entire cycle time. A rendezvous slot is defined as a
slot explicitly dedicated to a pair of nodes to communicate with
each other. In other words, the transmission right in the rendezvous slot is assigned to certain links (link scheduling). When messages for a particular node queued in its buffer cross threshold value the node will make some of its owned slots as rendezvous slots. Higher layer protocols are able to control the frequency of rendezvous slots.

### 3.1 Neighbor Discovery, Clustering and Synchronization

Frame synchronization is done by virtual clustering, as described in the S-MAC protocol\(^2\). When a node comes to life, it starts by waiting and listening. If it hears nothing for a certain period, it chooses a frame schedule and transmits a SYNC packet. The SYNC packet contains the time until the next frame starts. If the node during start up hears a SYNC packet from another node, it follows the schedule in that SYNC packet and transmits its own SYNC accordingly. Nodes retransmit their SYNC once in a while. When a node has a schedule (or schedules) but it hears SYNC with a different schedule from another node, it also adopts the new schedule. Adopting schedules of neighboring nodes ensures the successful communication between the nodes of different schedule. The described synchronization scheme, which is called virtual clustering\(^2\), urges nodes to form clusters with the same schedule. So, all the nodes in the networks need not to follow the same schedule.

During this virtual cluster creation, each node creates the one hop neighbor list and with using these a node can easily constitutes the two hop neighbor list. After that each node is given an id such that within a two hop neighbor the id is unique.

### 3.2 Slot Assignment

Each slot in H-MAC consists of a fixed length SYNC period, a fixed length data period (For RTS/CTS) and a sleep period that depends on the duty cycle. The duty cycle should be chosen in such a way that the sleep period of a slot is large enough to transmit a data packet along with ACK. All nodes are allowed to transmit in any slot, but the owner of the slot will get the priority. Priority can be ensured by choosing contention window size which is elaborately described in the part 3.5 of this paper.

The owner calculation can be performed by each sensor node locally by simple clock arithmetic. For example, if there are 8 neighbor nodes (every node is 1 or 2-hop neighbor to each other), the node 1 will be the owner of the Slot 1, 9, 17⋯ etc. The procedure is explained in Fig. 2 where T1, T2⋯, T10 represent the slot sequences and S1, S2⋯, S8 represent the sensor nodes. So according to the clock arithmetic (modulo 8) in Fig. 3, the sensor node S1 is the owner of the slot T1 and T9.

Now, each node can make some of its owned slot as a rendezvous slot with which it can send message to its neighbor exclusively. The rendezvous slots can be also calculated by clock arithmetic, as modulo m. The value of m is set according to the system requirements, i.e. network load, delay, message buffer size etc. m will be always multiple of node id. For instance, let node 1 wants to create a rendezvous slot. By using modulo 16, the rendezvous slots of node 1 will be a subset of \([1, 17⋯]\). The procedure is explained with the Fig. 4 where T9, T10⋯, T18 represent the slot sequences and S1, S2⋯, S8 represents the sensor nodes. If we use modulo 16, node S1 can make slot T17 as its rendezvous slot. Here it is noticeable that, though node S1 is owner of both slots T9 and T17 but S1 cannot make T9 as its rendezvous slot. It is because 9 is not a subset of \([1, 17⋯]\).

For the sake of scalability the value that we use in modulo operation i.e., m will be always larger than the number of two hop neighbor nodes in a virtual cluster. So when a new node wants to join in the network, at least there will be some slots which are not using as rendezvous and it will be used for the scalability.

### 3.3 Transmission

Each node will sleep for some time and then periodically wakes up to see whether any other node wants to talk to it. During sleeping, the node turns off its radio, and sets a timer to awake later. If a node wants to send data to another node it will check whether the node itself is the owner of the slot. If it is the owner of the slot it will get priority. If it is not owner of the slot it will contend with other nodes to get the slot. Broadcast packets are sent without Request-To-Send (RTS) and Clear-To-Send (CTS). Unicast packets will follow the sequence of RTS, CTS, Data, and Acknowledgement (ACK). This scheme is well recognized and used, for example in the IEEE 802.11 standard\(^18\).

Now, if messages for a particular node queued in its buffer cross threshold value the node will make some of its owned slots as rendezvous slots. The node will first broadcast the declaration of its making rendezvous slot. The declaration message contains how many slots will be used as rendezvous slot, and between whom the rendezvous will be done. So, remaining neighboring nodes can
The power adjustment features of H-MAC allow the sensor nodes to suitably vary the transmission power to reduce energy consumption. This idea is based on power control protocol for wireless ad-hoc network proposed in reference 19). H-MAC transmits the RTS and CTS packets with maximum power $P_{\text{max}}$. When receiver node receives an RTS packet, it responds with a CTS packet at usual maximum power level $P_{\text{max}}$. When the source node receives this CTS packet, it calculates $P_{\text{desired}}$ based on the received power level $P_r$ and transmitted power level $P_{\text{max}}$ as

$$P_{\text{desired}} = \frac{P_{\text{max}}}{P_r} \times R_{\text{sleep}} \times c$$

Where $R_{\text{sleep}}$ is the minimum necessary signal strength and $c$ is a constant. The source node uses power level $P_{\text{desired}}$ to transmit data packet. Similarly, receiver uses the signal power of received RTS packet to determine the power level to be used $P_{\text{desired}}$ for the ACK packet. This method assumes the attenuation between sender and receiver nodes to be the same in both directions. It also assumes the noise level at nodes to be below a certain predefined threshold value.

Since H-MAC allows data transmission between only one pair of nodes in a slot and all the neighbors of both sender and receiver sleep during transmission, it overcomes the shortcomings of said technique, like increased collision and degradation of network throughput.

3.5 Contention window size and owner’s priority

Owner’s priority can be set by using different contention window size for owners and non owners. Owners of a slot pick a random time uniformly over contention interval $[1, CW_{\text{owner}}]$, while non owners do so within $[1, CW_{\text{non}}]$. The average window size observed by an owner node would be $(1 + CW_{\text{owner}})/2$ and for the non owner would be $CW_{\text{non}} + (1 + CW_{\text{owner}})/2$. The owner takes hold of the channel every time because of its smaller contention window, provided that owner of the slot has some data to send. Once the slot is chosen, the node transmits at that slot. So, for both owner and non owner nodes, SYNC and RTS transmission in H-MAC always starts by waiting and listening for a random time within the contention interval. But when a slot is already declared as rendezvous slot for that slot without waiting for contention window the node can initiate transmission.

4. Energy Consumption Analytical Model

An analytical model for the energy consumption of nodes for H-MAC is explained in this section. For simplicity we consider the case where a sensor node is either in broadcast scheduling mode or in a link scheduling mode. Let $d$ be the duty cycle and $t_{\text{SIM}}$ be the simulation time and $t_{\text{TX}}, t_{\text{RX}}, t_{\text{IDLE}}, t_{\text{SLEEP}}, t_{\text{TRANS}}$ are denoted as the time spent for transmitting ($TX$ stands for transmission), receiving ($RX$ stands for reception), overhearing, idle listening, sleep, and radio transitions during sleep to wakeup state of a sensor node, respectively.
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So, \( t_{\text{SIM}} \) can be expressed as

\[
t_{\text{SIM}} = t_{\text{TX}} + t_{\text{RX}} + t_{\text{OH}} + t_{\text{IDLE}} + t_{\text{SLEEP}} + t_{\text{TRANS}} \tag{1}
\]

and

\[
t_{\text{SIM}} = t_{\text{SLOT}} \times N \tag{2}
\]

Here, \( N \) is total number of slots during time \( t_{\text{SIM}} \)

Again,

\[
t_{\text{SIM}} = t_{\text{w}} + t_{\text{r}} \tag{3}
\]

Where \( t_{\text{w}} \) and \( t_{\text{r}} \) represent period time while H-MAC operates in broadcast scheduling (\( w \) stands for without rendezvous) mode and link scheduling (\( R \) stands for rendezvous) mode respectively.

Let \( n_{\text{TX}}, n_{\text{RX}}, n_{\text{OH}}, n_{\text{ID}} \) represents the total number of times that a node hears, transmits, receives, and overhears during \( t_{\text{SIM}} \)

A sensor node consumes energy by transmitting \( (e_{\text{TX}}) \), receiving \( (e_{\text{RX}}) \), overhearing \( (e_{\text{OH}}) \), and idle listening \( (e_{\text{IDLE}}) \) during the awake state. And during the sleep state very less energy is consumed.

During transition \( (e_{\text{TRANS}}) \) from sleep state to active state energy is also consumed. Since our H-MAC protocol operate both in broadcast scheduling and link scheduling (Rendezvous) and we have used power adjustment technique, so transmitting energy is further divided into two category, without rendezvous, \( e_{\text{TX}(w)} \) and with rendezvous, \( e_{\text{TX}(r)} \). Similarly, receiving energy can be divided into \( e_{\text{RX}(w)} \) and \( e_{\text{RX}(r)} \).

Now energy consumption during \( t_{\text{SIM}} \) can be expressed by

\[
e = n_{\text{TX}(w)} \times e_{\text{TX}(w)} + n_{\text{TX}(r)} \times e_{\text{TX}(r)} + n_{\text{RX}(w)} \times e_{\text{RX}(w)} + n_{\text{RX}(r)} \times e_{\text{RX}(r)} + n_{\text{OH}} \times e_{\text{OH}} + n_{\text{ID}} \times e_{\text{IDLE}} + e_{\text{IDLE}} + e_{\text{SLEEP}} + e_{\text{TRANS}} + e_{\text{TRANS}} \tag{4}
\]

Since H-MAC has the probulation of adjusting transmission power we use maximum transmission power as \( E_{\text{TX}(\text{max})} \) and right transmission power as, \( E_{\text{TX}(\text{right})} \)

When a sensor node transmits a packet, it sends SYNC, RTS, DATA and it receives CTS and ACK.

So, for transmitting a packet energy consumed by a transmitting node is

\[
e_{\text{TX}(w)} = E_{\text{TX}(\text{max})} \times t_{\text{SYNC-RTS}} + E_{\text{TX}(\text{right})} \times t_{\text{DATA}} + E_{\text{TX}} \times t_{\text{CTS}} + E_{\text{TX}} \times t_{\text{ACK}} \tag{5}
\]

\[
e_{\text{TX}(r)} = E_{\text{TX}(\text{right})} \times t_{\text{SYNC}} + E_{\text{TX}(\text{right})} \times t_{\text{DATA}} + E_{\text{TX}} \times t_{\text{ACK}} \tag{6}
\]

Where \( t_{\text{SYNC-RTS}}, t_{\text{DATA}}, t_{\text{CTS}} \) and \( t_{\text{ACK}} \) are required time to send SYNC-RTS, DATA, and to receive CTS and ACK, respectively.

Now, when a sensor node receives a packet, it receives SYNC, RTS, DATA and it sends CTS and ACK.

So, for receiving a packet energy consumed by receiving node is

\[
e_{\text{RX}(w)} = E_{\text{RX}} \times t_{\text{SYNC}} + E_{\text{RX}} \times t_{\text{DATA}} + E_{\text{TX}(\text{right})} \times t_{\text{CTS}} + E_{\text{TX}(\text{right})} \times t_{\text{ACK}} \tag{7}
\]

\[
e_{\text{RX}(r)} = E_{\text{RX}} \times t_{\text{SYNC}} + E_{\text{RX}} \times t_{\text{DATA}} + E_{\text{TX}(\text{right})} \times t_{\text{CTS}} + E_{\text{TX}(\text{right})} \times t_{\text{ACK}} \tag{8}
\]

Now, let the sensor nodes Poisson arrival rate of transmitting packet is \( \mu_{\text{TX}} \) and sensor nodes Poisson arrival rate of receiving packet is \( \mu_{\text{RX}} \) during time \( t_{\text{SIM}} \).

So, the number of times the sensor node transmits and receives packet during \( t_{\text{SIM}} \) is

\[
n_{\text{TX}(w)} = \mu_{\text{TX}} \times t_{\text{SIM}(w)} \tag{9}
\]

\[
n_{\text{TX}(r)} = \mu_{\text{TX}} \times t_{\text{SIM}(r)} \tag{10}
\]

Similarly,

\[
n_{\text{RX}(w)} = \mu_{\text{RX}} \times t_{\text{SIM}(w)} \tag{11}
\]

\[
n_{\text{RX}(r)} = \mu_{\text{RX}} \times t_{\text{SIM}(r)} \tag{12}
\]

The overhearing of packets and idle listening occur during listen interval. So,

\[
n_{\text{OH}} = n_{\text{OH}}(\text{SYNC-RTS}) \times t_{\text{SYNC-RTS}} + n_{\text{OH}}(\text{CTS}) \times t_{\text{CTS}} \tag{13}
\]

and

\[
n_{\text{OH}} = n_{\text{H}} - n_{\text{RX}} \tag{14}
\]

\[
t_{\text{IDLE}} = d \times t_{\text{w}} - n_{\text{TX}(w)} \times (t_{\text{SYNC-RTS}} + t_{\text{CTS}}) - n_{\text{RX}(w)} \times (t_{\text{SYNC-RTS}} + t_{\text{CTS}}) - t_{\text{OH}} \tag{15}
\]

The transition from sleep mode to active mode will occur in every slot. So,

\[
t_{\text{TRANS}} = N \times t_{\text{Sl}} \tag{16}
\]

Where \( t_{\text{Sl}} \) represents the time required for switching radio from sleep mode to active mode.

So, the energy consumption of a sensor node can be computed analytically using the equation (4).

Now, we also develop energy consumption analytical model of S-MAC, one of the fundamental MAC protocol for sensor network, to compare with H-MAC. In fact S-MAC protocol is the most popular general purpose MAC protocol specially designed for wireless sensor network. For S-MAC the total simulation time, \( t_{\text{SIM}} \) can be expressed as

\[
t_{\text{SIM}} = t_{\text{TX}} + t_{\text{RX}} + t_{\text{OH}} + t_{\text{IDLE}} + t_{\text{SLEEP}} + t_{\text{TRANS}} \tag{17}
\]

And
\[ t_{SIM} = t_{SLOT} \times N \]  \hfill (18)

S-MAC protocol operates like broadcast scheduling and no power adjustment technique is used. Therefore energy consumption during \( t_{SIM} \) can be expressed as

\[
e = n_{TX} \times e_{TX} + n_{RX} \times e_{RX} + t_{OH} \times e_{OH} + t_{IDLE} \times e_{IDLE} + t_{SLEEP} \times e_{SLEEP} + t_{TRANS} \times e_{TRANS}
\]  \hfill (19)

When a node transmits a packet, it sends SYNC, RTS, DATA, and it receives CTS and ACK.

So, for transmitting a packet energy consumed by transmitting node is

\[
e_{TX} = E_{TX} \times (t_{SYNC-RTS} + t_{DATA}) + E_{RX} \times (t_{CTS} + t_{ACK})
\]  \hfill (20)

Now, when a node receives a packet, it receives SYNC, RTS, DATA, and sends CTS and ACK.

So, for receiving packet energy consumed by a receiving node is

\[
e_{RX} = E_{RX} \times (t_{SYNC-RTS} + t_{DATA}) + E_{TX} \times (t_{CTS} + t_{ACK})
\]  \hfill (21)

Let, sensor nodes Poisson arrival rate of transmitting packet and receiving packet during the time \( t_{SIM} \) are same as before.

So, the number of times the node transmits and receives packet during \( t_{SIM} \) is

\[
n_{TX} = \mu_{TX} \times t_{SIM}
\]  \hfill (22)

Similarly,

\[
n_{RX} = \mu_{RX} \times t_{SIM}
\]  \hfill (23)

The overhearing of packets and idle listening occur during listen interval. So,

\[
t_{OH} = n_{OH}(SYNC-RTS) \times t_{SYNC-RTS} + n_{OH}(CTS) \times t_{CTS}
\]  \hfill (24)

and

\[
n_{OH} = n_{OH} - n_{RX}
\]  \hfill (25)

\[
t_{IDLE} = d \times t_{SIM} - n_{TX} \times (t_{SYNC-RTS} + t_{CTS}) - n_{RX} \times (t_{SYNC-RTS} + t_{CTS}) + t_{OH}
\]  \hfill (26)

The transition from sleep to active mode will occur in every slot. So,

\[
t_{TRANS} = N \times t_{SA}
\]  \hfill (27)

So, the energy consumption of a sensor node of S-MAC can be computed analytically using equation (19). For simplicity we avoid considering the collision both for S-MAC and H-MAC in our analytical model.

Now, if we compare equation (5) & (6) with the equation (20) we see that the consumed power for a packet transmission for the source node is less in H-MAC than S-MAC. Similarly, if we compare equation (7) & (8) with equation (21) we see that the consumed power for a packet reception for the destination node is less in H-MAC than S-MAC. Finally if we put these value in equation (4) and (19) we can conclude that the H-MAC is more energy efficient than S-MAC.

We use topology 1 of Fig. 6 in order to validate our analytical model for energy consumption of H-MAC protocol. The parameters used for the analytical model are same as those used in the simulation. The power consumption for the transmission is 36 mW and the power required for receive and idle operation are 14.4 mW and power consumed during sleep is 15 \( \mu \)W\(^2\). We change the message inter arrival time in order to vary the traffic load. The result of analytical model for energy consumption of Node 1 in the topology 1 of Fig. 6 match with the simulation results, as shown in Fig. 7(a).

**5. Results and Discussion**

In this section, we investigate the performance of the proposed H-MAC protocol. We have simulated with Castalia, a simulator for Wireless Sensor Networks and Body Area Networks which is developed on the discrete event simulator OMNET\(^2\) which is developed on the discrete event simulator OMNET\(^+\). In the simulation setup, we take 100 nodes distributed in a 100 m \( \times \) 100 m area grid. The nodes are static and the radio range is chosen so that all the non-edge nodes have eight neighbors. The sink node is chosen on the bottom right corner of the network grid. The duty cycle is chosen 15 percent. The results are averaged over several simulation runs which are shown in Fig. 7. The parameters used for simulation are listed in **Table 1**.

We compare the performance of our proposed H-MAC protocol with the standard S-MAC protocol and T-MAC protocol and PH-MAC (Periodically Hybrid MAC) protocol. We took S-MAC and T-MAC protocol because they are widely accepted Medium Access Control protocol for Wireless Sensor Network. And the reason behind taking the PH-MAC protocol is that the PH-MAC is also a hybrid protocol which combines the TDMA and CSMA in order to achieve better performance. The performance metrics used in evaluation of H-MAC protocol are Energy consumption, Average
Packet Latency and Delivery ratio.

Energy consumption of sensor nodes for H-MAC, S-MAC, T-MAC and PH-MAC are shown in Fig. 7(b). We vary the packet generation interval from 1 to 10 seconds. We see that energy consumption per bit of H-MAC is less than the energy consumption of S-MAC and PH-MAC for different traffic load. It is because during heavy traffic H-MAC protocol makes some rendezvous slots. Energy consumption in rendezvous slot is less than the energy consumption of a slot of S-MAC as explained in section 3.3 of this paper. Besides the H-MAC protocol also uses the adjusted transmission power which further saves energy. And in comparison to T-MAC, during high traffic energy consumption of H-MAC is less than T-MAC. But as traffic declines H-MAC cannot create frequent rendezvous slot, hence its energy efficiency deteriorates. When the messages inter arrival period increases, the performance of H-MAC and T-MAC become almost equal. It is because T-MAC trades off latency for energy savings.

Average packet latency of sensor nodes for H-MAC, S-MAC, T-MAC and PH-MAC are shown in Fig. 7(c). We see that H-MAC achieve better delay performance compared to all other protocols. It is because link scheduling feature of H-MAC minimizes control signal during transmission and also when the protocol work in link scheduling it avoid the contention. However, since PH-MAC uses the TDMA its delay performance is better for heavy traffic load but with the decrease of the traffic its performance deteriorates significantly and it performs worst among all other protocols.

Table 1. Parameters for the MAC protocol

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel bandwidth</td>
<td>20 kbps</td>
</tr>
<tr>
<td>Data packet length</td>
<td>20 bytes</td>
</tr>
<tr>
<td>Transmission power</td>
<td>36 mW</td>
</tr>
<tr>
<td>Receive power</td>
<td>14.4 mW</td>
</tr>
<tr>
<td>Idle power</td>
<td>14.4 mW</td>
</tr>
<tr>
<td>Sleep state</td>
<td>15 μW</td>
</tr>
<tr>
<td>Frame length</td>
<td>1 sec</td>
</tr>
<tr>
<td>Threshold value for the buffer size (for H-MAC)</td>
<td>3 packet</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>15%</td>
</tr>
</tbody>
</table>

Fig. 7. Performance of the H-MAC protocol
Average packet delivery ratio is the ratio of the number of packet received to the number of packet sent over the entire node. Packet delivery ratio of sensor nodes for H-MAC, S-MAC, T-MAC and PH-MAC are shown in Fig. 7(d). Packet delivery ratio of T-MAC is the worst while performance of all other protocols is almost same. It should be noted here that, when the message inter arrival rate is greater than 4 second the PDR for H-MAC, PH-MAC and S-MAC crosses 70% which is acceptable in case of most of the application of sensor networks.

6. Conclusion and Future Work

This paper presents H-MAC; a novel energy efficient hybrid based medium access control protocol for wireless sensor networks. H-MAC uses the idea to combine the strength of contention based and schedule based approach of medium access control to achieve significant amount of energy savings. During heavy load H-MAC works by exploiting the idea of link scheduling (pair wise TDMA) which further improves the throughput by avoiding collision and message overhead. In addition, H-MAC saves energy by using transmission power adjustment. Besides, H-MAC also ensures fairness since every node has an owned slot where it gets priority and for non-owned slot each node gets equal priority during contention for a slot.

As a future work; we have a plan to implement our protocol on the mote hardware.

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