# A Scalable and Energy-Efficient Hybrid-Based MAC Protocol for Wireless Sensor Networks

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## ABSTRACT

The problem of MAC protocol design for wireless sensor networks poses many challenges such as energy constraint resources, strict wireless bandwidth, channel utilization … etc. These challenges make handling changes in network topology and network scalability a major issue. In this paper we present a new scalable and energy efficient hybrid-based MAC protocol for wireless sensor networks, abbreviated as SEHM. The protocol saves energy by reducing energy consumption due to idle listening and signal interference. Idle listening is reduced by making idle nodes and all nodes that have no data to send to switch early to sleep state. Signal interference is limited through using time division based medium access. Scalability of our approach is achieved through dividing the sensor network into clusters. Clusters are dynamically formed as all nodes in the sensor network are allowed to content for the position of a cluster head, to finally elect suitable cluster heads. The performance of our protocol is studied and analyzed by means of computer simulations, and we show that our approach outperforms S-MAC protocol in terms of energy consumption and packet delivery rate.

## Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication; C.2.2 [**Network Protocol**]: Protocol Architecture; D.4.8 [**Performance**]: Simulation.

## General Terms

Algorithms, Design, Performance.

## Keywords

Energy Efficiency, MAC Protocol, Scalability, Sensor Networks.

## 1. INTRODUCTION

Continues advances in micro-electro-mechanical systems, digital electronics, and wireless communications technologies have created low cost, low power, and multifunctional sensor devices, which can observe and react to changes in physical phenomena of their surrounding environments. The emergence of such sensors has led to the invention of Wireless Sensor Networks (WSNs). These sensor devices have limited energy resources and their functionality continues until their energy drains. Therefore, energy resources of sensor nodes should be managed wisely to extend its lifetime. As a result, energy efficiency has been considered the main and most important design key in WSNs.

As the radio transceiver unit is the major power consuming component of a typical sensor node [1], then large gain can be achieved at the link layer, where the MAC protocol controls the usage of the radio unit. Hence, a significant research effort has been devoted toward designing energy efficient MAC protocols. However, less attention has been put on designing MAC protocols that handle scalability and self organizability of sensor networks.

To design an efficient MAC protocol for WSNs, we have considered a set of attributes. First, the energy efficiency, sensor nodes are likely to be battery powered, and replacing or charging batteries is infeasible or not cost effective. Therefore prolonging lifetime of sensor nodes is a key issue. Second attribute that we consider is network scalability. Scalability is the quality of a network to optimally address the dynamics of operation conditions due to the changes in network size, node density, and topology, some sensor nodes may die over time, additional nodes may join the network …etc. Self organizability is another attribute that we address in our protocol, when deploying large scale sensor networks in hostile environments, self organization becomes important. Self organization means that a collection of sensor nodes be able to coordinate with each other to form a network that adapts well to changes to achieve a goal more efficiently.

Motivated by energy efficiency, scalability, self organizability, and robustness, we propose a new MAC layer protocol for large sensor networks named as SEHM. Our protocol is composed of two phases; cluster formation phase, and data transfer phase. During the clustering phase, sensor nodes are grouped in clusters, each cluster is controlled by a Cluster Head (CH). Cluster formation is done through the invocation of a clustering algorithm similar to Ext-HEED algorithm [2] with a slight modification. Both Residual energy and communication cost are used in CHs selection. Only sensors that have a high residual energy can become cluster head nodes. Upon the completion of the clustering algorithm, the data transfer phase starts. The data transmission is divided into two parts; report collected sensory data from sensors to CHs, then from CHs to the Base Station (BS). During intra-cluster communication (i.e. collecting data from sensor nodes), the channel access is controlled by the CH. After the reception of the synchronization (SYNC) message, all nodes within the cluster that have data to send content for the channel to send their

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requests to the CH. Then, CHs schedule and distribute the access to the shared wireless medium between nodes within clusters. Finally, CHs use a TDMA schedule distributed by the BS station to report their data.

The rest of this paper is organized as follow: We present and discuss some related work in section 2. Section 3 describes our protocol scheme. In section 4 the protocol performance is evaluated through simulation. Finally, we conclude the paper and present future work in section 5.

## 2. RELATED WORK

Power management of the radio transceiver unit of a wireless device has gained significant importance with the emerging of wireless sensor networks since the radio unit is the major consumer of the sensor's energy [1]. It has been shown that the energy consumed in transmitting one bit is several thousand times more than the energy consumed in executing one instruction [1]. Recently, several MAC layer protocols have been proposed to reduce the energy consumption of the sensor's radio unit. Protocols presented in [3], [4], [5], and [6] are some examples.

MAC protocols in wireless sensor networks can be classified into three general groups: scheduled, unscheduled, and hybrid protocols. Scheduled MAC protocols attempt to organize the communication between sensor nodes in an ordered way. The most common scheduling method which organizes sensor nodes in slots is Time Division Multiple Access (TDMA), where each sensor node is assigned a time slot. Organizing sensor nodes provides the capability to reduce collisions and message retransmissions at the cost of a fine grained synchronization and state distribution. Unscheduled protocols attempt to conserve energy by allowing sensor nodes to operate independently with minimum of complexity. In addition unscheduled MAC protocols typically do not share information or maintain states. These benefits come at the cost of collisions and idle listening which may occur and cause degradation in the protocol efficiency. Hybrid MAC protocols combine the strengths of scheduled and unscheduled MAC protocols while avoiding their weakness to better address the special requirements of wireless sensor networks MAC protocols. The greatest advantage of the hybrid MAC protocols comes from its easy and rapid adaptability to traffic conditions which can save a large amount of energy.

The most widely used MAC protocol for WSN is S-MAC [3]. S-MAC introduces a low duty cycle operation in multi-hop wireless sensor networks, where the nodes spend most of their time in sleep mode to reduce energy consumption. Under variable traffic loads S-MAC does not perform well as proved by [4].

As a contention based MAC protocol, S-MAC has a main drawback that is the probability of collision increases as the network size and/or load increases, which degrades channel utilization and wastes energy. This motivates our research on scalable hybrid based medium access schemes. Next sections describe and discuss our SEHM protocol.

## 3. SEHM PROTOCOL SCHEME

SEHM Protocol scheme consists of two components; clustering algorithm and a channel access mechanism. Details are given in the following subsections.

### 3.1 Clustering Algorithm

Sensor network clustering is done through the execution of a similar Ext-HEED algorithm with a slight modification [2]. Ext-HEED is originally inspired by HEED algorithm [7]. Election of CHs is based on two main criteria; first the amount of residual energy of the node, thus a node with high residual energy has a higher chance to be elected and become a CH. Second criterion is the intra-cluster communication cost. This criterion used by nodes to determine the cluster to join. This is especially useful if a given node falls within the range of more than one CH. This algorithm has four main characteristics:

- The probability that two nodes within each other's transmission range becoming cluster heads is small.
- For a given sensor's transmission range, the probability of cluster head selection can be adjusted to ensure inter-cluster head connectivity.
- All nodes are assumed to be equally significant and energy consumption is not uniform among nodes.
- Nodes that did not hear from any cluster head (called orphaned nodes) should re-execute the algorithm which decreases the cluster head count.

The clustering algorithm achieves its task through the execution of the following four phases:

***Initialization phase.*** Initially the algorithm sets a certain number of cluster heads among all sensors. This value is used to limit the initial cluster head announcements to the other sensors. As well each sensor sets its probability of becoming a cluster head.

***Repetition phase.*** During this phase, every sensor node goes through several iterations until it finds the cluster head that it can transmit to with the least transmission power. Finally, each sensor doubles its cluster head probability value and goes to the next iteration of this phase. It stops executing this phase when its cluster head probability reaches 1.

***Optimization phase.*** In this phase, all uncovered nodes must run the original HEED algorithm [7] to elect some extra cluster heads. Each uncovered node selects a node with the highest priority in its neighborhood (including itself) as a cluster head to cover itself. Reducing cluster head count reduces the inter-cluster head communication and thus prolongs the network lifetime and limits the data collection latency.

***Finalization phase.*** During this phase, each sensor makes a final decision on its status. It either picks the least cost cluster head or pronounces itself as a cluster head.

### 3.2 Channel Access Mechanism

SEHM protocol schedules and distributes the channel access between sensor nodes by following design principle of our previous QE-MAC protocol presented in [8] with some improvements. Other related approaches are presented on [9] and [10]. This approach combines the CSMA and TDMA schemes and utilizes the advantages of both mechanisms while avoiding their shortcomings to gain a save in energy. The channel access is done by providing scheduled dynamic slots with no contention (based on TDMA) for data messages and random access slots (based on CSMA/CA) for control messages.

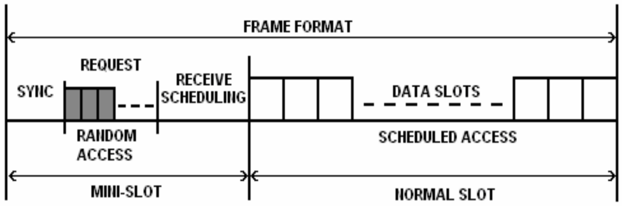

**Figure 1. Frame Structure: sensor node has data to send**

After the execution of the clustering algorithm, the CH in each cluster is responsible for controlling and distributing the channel access between sensor nodes within the cluster, and then reports gathered sensory data into the Base Station (BS). The communication process is composed of two steps; transferring data from sensor nodes to cluster heads (*intra-cluster communication*), then from cluster heads to the base station. Here, before going further in the description of our protocol, we define some assumptions:

- All sensor nodes are in the radio range of the BS.
- Always we consider the number of heads generated by the cluster head after each round is fixed.
- The clustering algorithm is repeated every certain period (in our implementation is set to 50 seconds) to re-elect new CHs in order to evenly distribute the consumed energy between sensor nodes. (i.e. the role of CH is rotated between nodes according to the residual energy of each node)
- Inter-cluster communication is only allowed between BS and CHs. CHs are not allowed to communicate with each other.

### *3.2.1 Intra-Cluster Communication*

Data Transmission inside cluster is controlled by the CH. The channel access mechanism is based on dividing communication time into frames (see Fig. 1). Each frame is composed of two slots: *mini slot* and a *dynamic normal slot*. Mini-slot is used to transmit and receive control signals, and consists of three parts; *Frame Synchronization (SYNC), Request,* and *Receive Scheduling*. Dynamic Normal slot is used to control the transmission of the gathered data to cluster head. The frame length is dynamic (i.e. the number of time slots is increased or decreased according to the number of nodes that have data to send).

Our SEHM scheme accomplishes its task through the following four phases: *Synchronization, Request, Receive Scheduling,* and *Data Transfer*. Nodes that have data to send should content for the channel during the *Request* phase and send their requests to the CH. (The contention interval should be long enough to give all sensor nodes within the cluster, that have data to send, a chance to send their requests). Then, sensor nodes use the TDMA slots distributed by the CH to send their data during the data transfer phase to CHs. Sensor nodes that have no data to transmit go to sleep directly after the end of the mini-slot (see Fig. 2).

More details are given below about the operation of the protocol in each phase:

- ***Synchronization phase:*** At the beginning of each frame, the CH broadcasts a SYNC message to all sensor nodes within its cluster – all sensor nodes should be in receive mode during this phase to be able to capture the SYNC message. The SYNC message contains synchronization information for the packet transmission.
- ***Request phase:*** During this phase, sensor nodes that have data to transmit content for the channel in order to acquire the access to send its request to the CH.
- ***Receive Scheduling phase:*** The CH broadcasts a scheduling message to all sensor nodes within its cluster that contains the TDMA slots for the subsequent phase "*data transfer phase*". All sensor nodes that have no data to transmit or receive should turn their radios transceivers off and enter sleep mode until the beginning of next frame. Making sensor nodes sleep early results in significant save in energy.
- ***Data Transfer phase:*** In this phase, sensor nodes use the TDMA slots to transmit their data to the CH or to communicate with their neighbors.

At the beginning of each frame all sensor nodes within the cluster should be awake to capture the SYNC packet and to keep them timely synchronized.

### *3.2.2 Reporting Data to the Base Station*

Accessing the channel to report data to the base station nearly uses the same frame structure used in intra-cluster communication. As the number of CHs is fixed after each execution of the clustering algorithm, then the BS schedules directly the cluster heads, and distributes the time slots between CHs. We assume that all CHs have data to report to the BS. As a result, the random access period is removed, and the frame structure becomes as shown in Fig. 3.

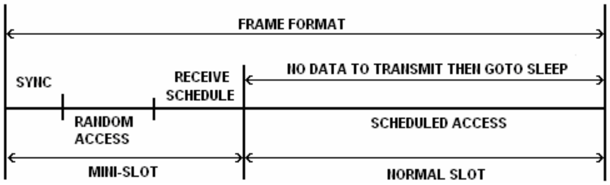

**Figure 2. Frame Structure: node has no data to send**

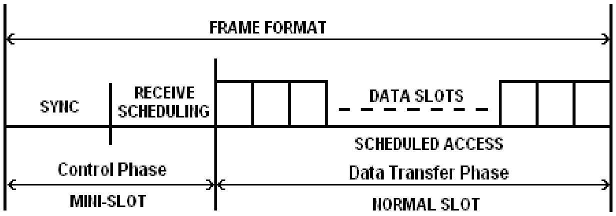

**Figure 3. Frame Structure ( Used in inter-communication between cluster heads and base station)**

The communication procedure is done through the following phases:

- ***Synchronization phase:*** At the beginning of each frame, the BS broadcasts a SYNC message to all sensor nodes – all sensor nodes should be in receive mode during this phase to be able to capture the SYNC message. The SYNC message contains synchronization information.
- ***Receive Scheduling phase:*** as CHs are announced after executing the clustering algorithm, then the BS knows the current elected CHs. As a result, there is no need for CHs to content for the channel to acquire the access to send their request messages. Moreover, we assume that CHs always have data to report to the BS. The BS broadcasts a scheduling message to all CHs that contains the TDMA slots for the subsequent phase "*data transfer phase*".
- ***Data Transfer phase:*** In this phase, CHs use the received TDMA schedule to transmit their collected data to the BS.

# 4. PERFORMANCE EVALUATION

To study and evaluate the performance of our protocol, we did a comparative study with S-MAC protocol. We have used SensorSimulator framework [11]. SensorSimulator is developed on the discrete event simulator OMNeT++ [12], mainly intended to support sensor network simulations. The simulator contains a model of the EYES wireless sensor node [13]. The EYES node consists of a 16-bit embedded processor (Texas Instruments MSP430F149), a low power radio (RFM TR1001, 868.35 MHz, hybrid transceiver), a 2-Mbit EEPROM memory, and various connectors to interface to outside world. A node runs from 3V power source supplied by two AA size batteries.

**Table 1. Simulation Parameters**

| | |
|---|---|
| **General** | |
| Message payload | 25 bytes |
| Data length | Up to 250 bytes |
| **Radio** | |
| Effective data rate | 115 kbps |
| Transmit | 12 mA |
| Receive | 3.8 mA |
| Sleep | 0.7 µA |
| **S-MAC** | |
| Frame length | 610 ms |
| Contention Window (CW) | 15 ms |
| Active period | 60ms |
| **SEHM** | |
| Slots in SYNC phase ($N_1$) | 10 |
| Slots in scheduling phase ($N_2$) | 50 |
| Slots in Random access period ($N_3$) | 45 |
| Slots in data transfer phase ($N_4$) | 40 |
| Frame length | $(N_1+N_2+N_3)/3 + N_4$ |

The OMNeT++ model has the same limits as the EYES nodes have. Energy consumption in the model is based on the amount of energy the radio consumes. The consumed energy by the CPU as a result of the protocol execution is not taken into account.

In this section we investigate the performance of the proposed SEHM protocol in clustered network topology and compare it against S-MAC. The metrics that are used to assess the performance of the protocols are: *Average Energy Consumed, Average Packet Delivery Ratio,* and *Average Packet Delay*.

The simulation setup includes 500 nodes randomly scattered on a field of approximately 500m x 500m. All sensor nodes are within the radio range of the BS. The simulation is allowed to run for 2000 seconds and the results are averaged over several simulation runs. In our simulation experiments, we evaluate the performance of our SEHM protocol and compare it with the standard S-MAC with 10% duty cycle. The simulation parameters are given in Table 1.

## 4.1 Energy Consumption

Energy efficiency is the most important performance metric in wireless sensor networks. The comparative energy consumption for the two protocols is illustrated in Fig. 4. The energy consumption values for S-MAC are averaged over all active and sleep intervals and compared them with those of SEHM protocol. SEHM protocol, as expected, outperforms S-MAC protocol. This is because S-MAC is a contention-based protocol, where the collision rate is increasing as the traffic rate increases, which leads to consume more energy due to retransmitting collided packets. SEHM adapts better to the increase in the traffic rate; resulting in, on average consumes less energy when compared to S-MAC.

## 4.2 Average Packet Delay

Fig. 5 shows the average packet delay for S-MAC and SEHM protocols. In this experiment, we vary the traffic load by changing the packet generation time on the source node. The packet generation time changes from 1sec to 16sec. It is evident that the average delay time of contention based protocols (S-MAC) are less than that of scheduled based protocols (SEHM). This is because of the delay introduced by random scheduling and clustering overhead in SEHM.

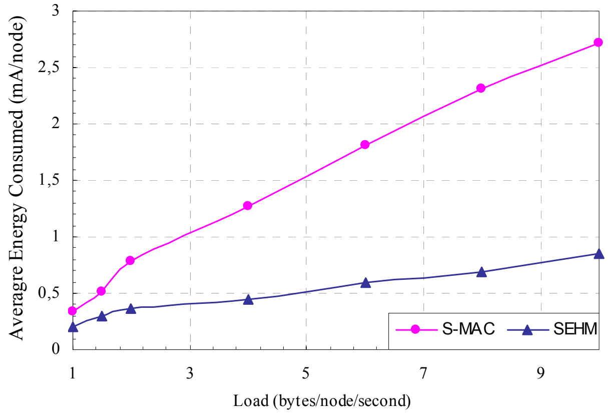

**Figure 4. Average Energy Consumption**

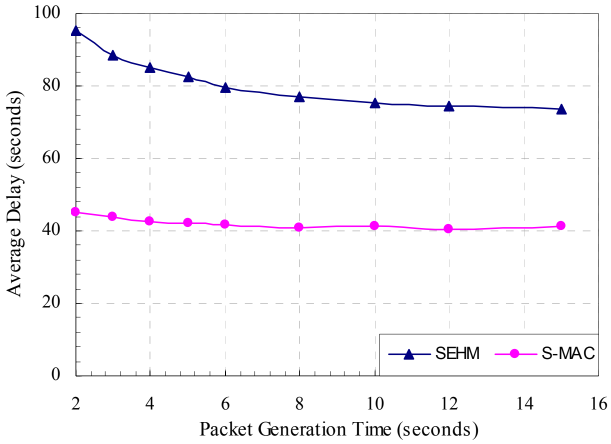

**Figure 5. Average Delay**

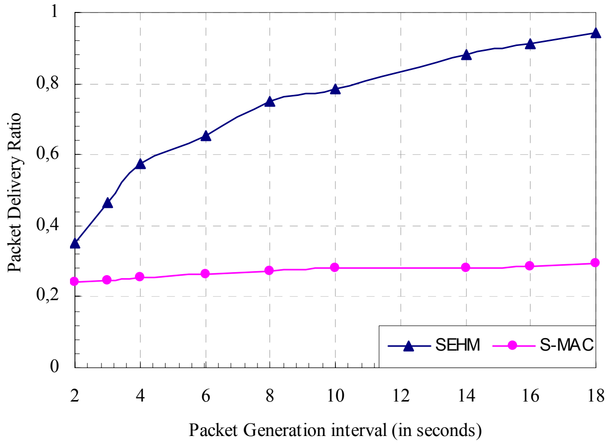

**Figure 6. Average Delivery Ratio**

### 4.3 Packet Delivery

Fig. 6 shows the average packet delivery ratio of variable traffic packets successfully delivered to sink nodes. As our SEHM protocol is a collision free MAC protocol, it outperforms S-MAC. As S-MAC is a contention based MAC protocol it suffers from higher rate of collisions especially for high data traffic, then successfully received packets are decreased.

## 5. CONCLUSION AND FUTURE WORK

In this paper, we presented SEHM protocol, a new clustering based energy efficient and scalable hybrid medium access control scheme for large scale wireless sensor networks. SEHM protocol combines the benefits of contention based and scheduled based protocols to achieve a significant amount of energy savings. SEHM enables only those nodes which have data to transmit to access the channel; this avoids wasting slots by excluding those nodes which have no data to transmit from the TDMA schedule, and to switch nodes to sleep mode when they are not included in the communication process. SEHM protocol accommodates well to traffic and topology changes, and achieves a good scalability through network clustering.

Through computer simulations, we studied the performance of our protocol and compared it against S-MAC protocol. Simulation results demonstrated that SEHM protocol outperforms S-MAC protocol in terms of energy efficiency and packet delivery ratio which are very important issues in wireless sensor networks.

As a future work, we are intended to integrate a data aggregation method at the level of cluster head to remove data redundancy, and hence enhancing protocol performance.

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