Energy Efficient Medium Access Protocol for Clustered Wireless Sensor Networks

K. N. Shreenath and K. G. Srinivasa

Abstract Wireless sensor networks use battery-operated computing and sensing devices. A network of these devices will collaborate for a common application such as environmental monitoring. We expect sensor networks to be deployed in an ad hoc fashion, with individual nodes remaining largely inactive for long periods of time, but then becoming suddenly active when something is detected. These characteristics of sensor networks and applications motivate a MAC that is different from traditional wireless MACs such as IEEE 802.11 in almost every way: energy conservation and self-configuration are primary goals, while per-node fairness and latency are less important. In this proposal, we present a new MAC layer protocol for cluster based wireless sensor networks that reduces energy consumption and provides Quality of Service (QoS) through the use of service differentiation concept. The proposed protocol consists of two parts: First part is responsible for classifying gathered data at sensor nodes based on its importance and then stores it in the appropriate queue of the node's queuing system. The second part is responsible for energy efficient medium access mechanism that uses both scheduled and unscheduled schemes to gain a save in energy, and hence extending network's lifetime. The save in energy is achieved by differentiating between control and data messages. Data messages are assigned scheduled slots with no contention, while short control messages are assigned random access slots.

Keywords Sensor · Energy · Efficient · Scheduled · MAC · TDMA · Clustering

K. N. Shreenath (✉)
Department of CSE, Siddaganga Institute of Technology,
Tumkur, India
e-mail: shreenathk_n@yahoo.co.uk

K. G. Srinivasa (✉)
Department of CSE, M S Ramaiah Institute of Technology, Bangalore, India
e-mail: srinivasa.kg@gmail.com

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1 Introduction

Wireless sensor networking is an emerging technology that has a wide range of potential applications including environment monitoring, smart spaces, medical systems and robotic exploration. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Each node has one or more sensors, embedded processors and low-power radios, and is normally battery operated. Typically, these nodes coordinate to perform a common task.

Medium access control (MAC) is an important technique that enables the successful operation of the network. One fundamental task of the MAC protocol is to avoid collisions so that two interfering nodes do not transmit at the same time. There are many MAC protocols that have been developed for wireless voice and data communication networks. Typical examples include the time division multiple access (TDMA), code division multiple access (CDMA), and contention-based protocols like IEEE 802.11.

A good MAC protocol should have the following attributes. The first is the energy efficiency. Sensor nodes are likely to be battery powered, and it is often very difficult to change or recharge batteries for these nodes. Prolonging network lifetime for these nodes is a critical issue. Another important attribute is the scalability to the change in network size, node density and topology. Some nodes may die over time; some new nodes may join later; some nodes may move to different locations. The network topology changes over time. A good MAC protocol should easily accommodate such network changes.

Energy constraints of sensor networks have demanded energy awareness at most layers of the networking protocol stack. Provided that the radio transceiver unit considered as the major consumer of energy resource of the sensor node especially when the radio transceiver is turned on all time, then a large amount of energy savings can be achieved through energy efficient media access control mechanisms. For this reason, energy consideration has dominated most of the research at MAC layer level in wireless sensor networks. The concepts of latency, throughput and delay were not primary concerns in most of the presented work on sensor networks.

We propose a new energy efficient medium access control mechanism with quality of service support for cluster based wireless sensor networks. It uses a both scheduled (TDMA) and contention based (CSMA) medium access schemes. It differentiates between short and long messages; long data messages are assigned scheduled TDMA slots, while short periodic control messages are assigned random access slots. This technique limits message collisions and reduces the total energy consumed by the radio transceiver. Perhaps the greatest advantage is the efficient node's battery usage and its support for quality of service based on the service differentiation concept. The service differentiation is done through data prioritization to distinguish between four different priority levels based on traffic importance and criticality, while maintaining energy efficient usage of the sensor node's battery. It handles highest priority data packets differently than those of lowest priority. If the packet to be delivered is an urgent data packet that should be processed immediately without any delay, then the sensor node puts this packet into its high priority queue of its queuing system. This allows sensor nodes to do some type of traffic management and provide extremely highest priority traffic a greater chance of acquiring the channel and hence rapidly served with minimum delay.

2 Related Work

The medium access control protocols for the sensor networks can be classified broadly into two categories: Contention based and Schedule based.

2.1 Contention Based

The contention based protocols relax time synchronization requirements and can easily adjust to the topology changes as some new nodes may join and others may die few years after deployment. These protocols are based on Carrier Sense Multiple Access (CSMA) technique and have higher costs for message collisions, overhearing and idle listening.

The IEEE 802.11 [1] is a well-known contention based medium access control protocol which uses carrier sensing and randomized back-offs to avoid collisions of the data packets. The Power Save Mode of the IEEE 802.11 protocol reduces the idle listening by periodically entering into the sleep state. This PSM mode is for the single-hop network where the time synchronization is simple and may not be suitable for multi-hop networks because of the problems in clock synchronization, neighbor discovery and network partitioning.

Power Aware Multi-Access [2] is one of the earliest contention based MAC protocol designed with energy efficiency as the main objective. In this protocol nodes which are not transmitting or receiving are turned off in order to conserve energy. This protocol uses two separate channels for the data and control packets. It requires the use of two radios in the different frequency bands at each sensor node leading to the increase in the sensors cost, size and design complexity. Moreover, there is significant power consumption because of excessive switching between sleep and wakeup states.

Sensor—MAC [3] a contention based MAC protocol is modification of IEEE 802.11 protocol specially designed for the wireless sensor network. In this medium access control protocol, the sensor node periodically goes to the fixed listen/sleep cycle. A time frame in S-MAC is divided into two parts: one for a listening session and the other for a sleeping session. Only for a listen period, sensor nodes are able to communicate with other nodes and send some control packets.

Timeout T-MAC [4] is the protocol based on the S-MAC protocol in which the Active period is preempted and the sensor goes to the sleep period if no activation event has occurred for a particular time period. The event can be reception of data, start of listen/sleep frame time etc. The energy consumption in the Timeout T- MAC protocol is less than the Sensor S-MAC protocol. But the Timeout T-MAC protocol has high latency as compared to the S-MAC protocol.

2.2 Scheduled Based

The schedule based protocol can avoid collisions, overhearing and idle listening by scheduling transmit and listen periods but have strict time synchronization requirements.

The traffic adaptive medium access (TRAMA) [5] is a Contention based protocol that has been designed for energy efficient collision free channel in WSNs. In this protocol the power consumption has been reduced by ensuring collision free transmission and by switching the nodes to low power idle state when they are not transmitting or receiving.

SMACS [6] is a schedule based medium access control protocol for the wireless sensor network. This MAC protocol uses a combination of TDMA and FDMA or CDMA for accessing the channel. In this protocol the time slots are wasted if the sensor node does not have data to be sent to the intended receivers. This is one of the drawbacks of this MAC scheme.

Low Energy Adaptive Clustering Hierarchy (LEACH) is a energy aware scheduled based MAC [7] protocol assumes the formation of clusters in the network. The cluster head manages each of the cluster sensor nodes. The cluster head collects the information from the other sensor nodes within its cluster, performs the data fusion, communicates with the other cluster head and finally sends the data to the control center. The cluster head performs the assignment of the time slots to the sensor nodes within its cluster. The cluster head inform the other nodes about the time slot when it should listen to other nodes and the time slot when it can transmit own data.

Hybrid MAC protocols combine the strengths of scheduled and unscheduled MAC protocols while compensating their weakness to build more efficient MAC schemes. Hybrid protocols use different techniques to conserve sensor battery power; some protocols differentiate between small and long data messages. Long data messages are assigned scheduled slots with no contention, whereas small periodic control messages are assigned random access slots. Other hybrid techniques adjust the behavior of MAC protocol between CSMA and TDMA depending on the level of the contention in the network. 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, but this advantage comes at the cost of the protocol overhead and complexity caused by the TDMA structure which limits the scalability and applicability range of the protocol.

In [8], authors propose Q-MAC scheme that attempts to minimize the energy consumption in a multi-hop wireless sensor network, while providing quality of service by differentiating network services based on priority levels. The priority levels reflect the criticality of data packets originating from different sensor nodes. The Q-MAC accomplishes its task through two steps, intra-node and inter-node scheduling. The intra-node scheduling scheme adopts a multi-queue architecture to classify data packets according to their application and MAC layer abstraction. Inter-node scheduling uses a modified version of MACAW [9] protocol to coordinate and schedule data transmissions among sensor nodes.

Our MAC uses a more energy efficient way to coordinate and schedule data transmissions among clustered sensor nodes by utilizing both scheduled and unscheduled schemes.

3 Protocol Description

Our MAC protocol is composed of two parts.

The first part uses a modified version of the queuing architecture of Q-MAC. It classifies packets based on their importance and stores them into the appropriate queue. The source node knows the degree of the importance of each data packet it is sending which can be translated into predefined priority levels. The application layer sets the required priority level for each data packet by appending two extra bits at the end of each data packet (Fig. 1). The number of bits used to distinguish priorities could be set according to the number of priority levels required.

The queuing architecture of the Q-MAC is composed of four queues (Fig. 2). Each packet is placed in one of the four queues—high, medium, normal, or low based on the assigned priority. During transmission, the MAC transmits according to the priority of the data packet.

The second part adapts scheduled and unscheduled schemes in an attempt to utilize the strengths of both mechanisms to gain a save in energy resources of the sensor node, and hence prolonging the lifetime of the sensor network. It provides scheduled slots with no contention (based on TDMA) for data messages and random access slots (based on CSMA/CA) for periodic control messages. In the design of protocol, we assume that the underlying synchronization protocol can provide nearly perfect synchronization, so that synchronization errors can be neglected.

MAC classifies sensor nodes within the sensor network into clusters. For clustering in the sensor network, we can use different types of algorithms like heuristics, weighted, hierarchical, grid schemes. For our MAC protocol we are using an hierarchical scheme called Energy Efficient Clustering Scheme (EECS) [10].

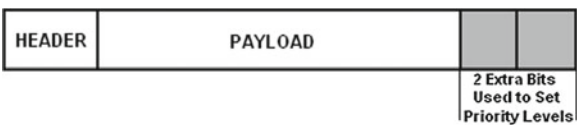

Fig. 1 Data packet format

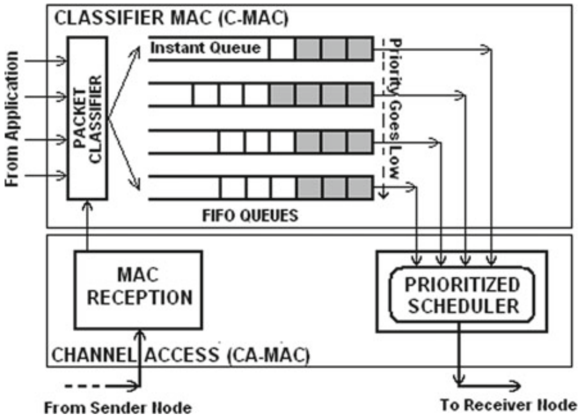

Fig. 2 Q-MAC structure

An EECS is a clustering algorithm in which cluster head candidates compete for the ability to elevate to cluster head for a given round. This competition involves candidates broadcasting their residual energy to neighboring candidates. If a given node does not find a node with more residual energy, it becomes a cluster head. Cluster formation is different than that of LEACH. LEACH forms clusters based on the minimum distance of nodes to their corresponding cluster head. EECS extends this algorithm by dynamic sizing of clusters based on cluster distance from the base station. The result is an algorithm that addresses the problem that clusters at a greater range from the base station require more energy for transmission than those that are closer. Ultimately, this improves the distribution of energy throughout of the network, resulting in better resource usage and extended network lifetime. The Cluster head node is responsible for controlling the channel access between sensor nodes and collects sensory data from them.

The transmission mechanism of MAC is based on dividing communication time into frames, which are controlled by the head node (Fig. 3). The frame is composed of two periods: contention period and normal period. Contention period is used to transmit and receive control signals, and consists of three parts; Frame Synchronization (SYNC), Request, and Receive Scheduling. Normal period is used to control the transmission of the gathered sensory data to head node.

Our proposed MAC accomplishes its task through the following four phases: Synchronization, Request, Receive Scheduling, and Data Transfer. Nodes that have data

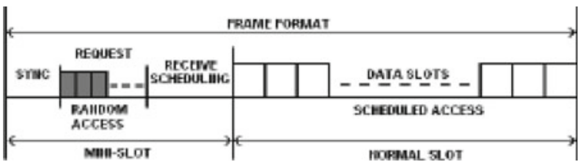

Fig. 3 Frame format of proposed MAC

to send should contend for the channel during the Request phase and send their requests along with the appropriate priority level of its traffic to the cluster head. Then, sensor nodes use the TDMA slots during the data transfer phase to send their data packets. The details are given below.
Synchronization phase: At the beginning of each frame, the head node broadcasts a SYNC message to all sensor nodes. All sensor nodes should be in receiving 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 contend for the channel in order to acquire the access to send its request to the head node along with the required priority level. The Fig. 4 shows the request message structure.
Receive Scheduling phase: The head node broadcasts a scheduling message to all sensor nodes that contains the TDMA slots for the subsequent phase data transfer phase. In this phase all sensor nodes should be in receive mode. Here, the cluster head should take into account the required priority levels when assigning TDMA slots to sensor nodes.
Data Transfer phase: In this phase, sensor nodes use the TDMA slots to transmit their data to the cluster head or to communicate with their neighbors. All sensor nodes that have no traffic to transmit or receive should turn their radio transceivers off and goes to sleep mode.

4 Performance Analysis

To study and evaluate the performance of the proposed MAC protocol, we have used NS2 sensor network simulator. The NS-2 simulation environment is a flexible tool for network engineers to investigate how various protocols perform with different configurations and topologies.
We evaluate the performance of the proposed protocol in a static single hop network topology. Energy consumption and average delay are the performance metrics used in the evaluation. The setup of experiments includes 100 nodes on a field of 100×100 m. The simulated nodes are within the radio range of each other. The simulation is allowed to run for 500 s and the results are averaged over several simulation runs. In simulation, we evaluate the performance of our proposed MAC and compare it with the standard S-MAC and Q-MAC. The simulation parameters are given in the Table 1.

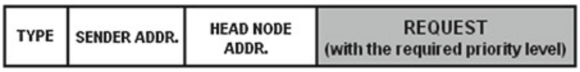

Fig. 4 Request message format

Table 1 Simulation parameters

General		**S-MAC**	
Message payload	25 bytes	Frame length	610 ms
Data length	Up to 250 bytes	Contention window (CW)	15 ms
		Active period	300 ms
Radio			
Effective data rate	115 kbps	**Proposed MAC**	
Transmit	12 mA	Slots in SYNC phase (N1)	10
Receive	3.8 mA	Slots in scheduling phase (N2)	100
Sleep	0.7 μA	Slots in random access period (N3)	70
		Mini-slot time	1 ms
Q-MAC		Normal slot time	3 ms
Frame length	610 ms	Slots in data transfer phase (N4)	85
Contention period	300 ms	Frame length (N1+N2+N3)/3	+ N4
Contention window	15 ms		
Short space (SS)	0.5 ms		
Frame space (FS)	1 ms		

4.1 Energy Consumption

Energy efficiency is the most important performance metric in wireless sensor networks. The Fig. 5 shows the comparative energy consumption for the proposed MAC, S-MAC and Q-MAC. The proposed MAC protocol is more energy efficient than S-MAC and Q-MAC protocols. The proposed MAC protocol adapts better to the increase in the traffic rate and consumes less energy when compared to the other two protocols.

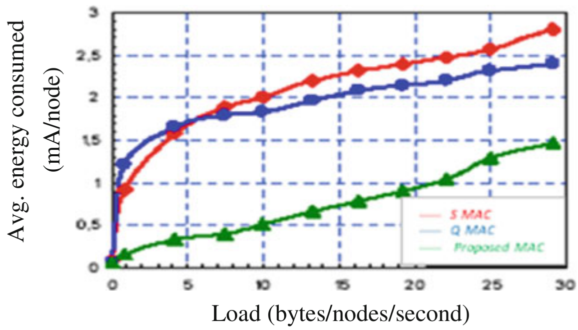

Fig. 5 Average energy consumption

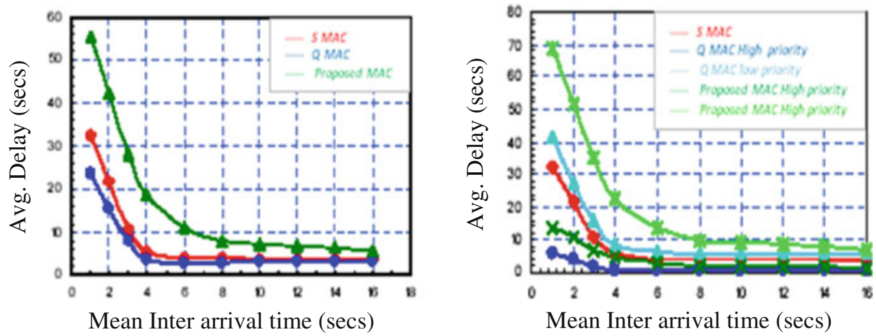

Fig. 6 Average packet delay (non prioritized and prioritized traffic)

4.2 Average Packet Delay

The Fig. 6 shows the average packet delay under normal and prioritized traffic. In the evaluation, we vary the traffic load by changing the packet inter-arrival time on the source node. The packet inter-arrival time changes from 1 to 16 sec. It is observed that the average delay time of contention based protocols are less than that of scheduled based protocols. This is because of the latency introduced by random scheduling. The results of prioritized traffic indicate that Proposed MAC successfully differentiates network services like Q-MAC. The higher priority packets are always accompanied with low latency. Therefore our MAC protocol achieves high energy efficiency under wide range of traffic loads and priorities.

5 Conclusion

We proposed a new energy efficient medium access control scheme for cluster based wireless sensor networks. The MAC combines the benefits of contention based and scheduled based protocols to achieve a significant amount of energy savings and offers QOS by differentiating network services based on priority levels. It enables only the nodes which have a data to transmit to access the channel according to their traffic priority levels; 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.
Prioritizing traffic according to its importance and criticality provides a greater chance for extremely highest priority nodes to access the channel and acquire the medium and hence rapidly served with minimum delay.

References

1. IEEE (1999) Wireless LAN medium access control (MAC) and physical layer specifications, 1999 edn. ANSI/IEEE Standard 802.11
2. Singh S, Raghavendra C (1998) PAMAS: power aware multi-access protocol with signaling for ad-hoc network. ACM SIGCOMM Computer Communication Review, July
3. Ye W, Heidemann J, Estrin D (2002) An energy-efficient MAC protocol for wireless sensor networks, IEEE INFOCOM, vol 2. New York, pp 1567–1576
4. van Dam T, Langendoen K (2003) An adaptive energy efficient MAC protocol for wireless networks. In: Proceedings of the first ACM conference on embedded networked sensorsystems. ACM Press, New York
5. Rajendran V, Obraczka K, Gracia-Luna-Aceves JJ (2003) Energy efficient, collision free medium access control for wireless sensor networks. In: ACM international conference on embedded networked sensor systems (SenSys), pp 181–192
6. Sohrabi K, Gao J, Ailawadhi V, Pottie GJ (2000) Protocols for self organization of a wireless sensor network. IEEE Pers Commun 7(5):16–27
7. Arisha K, Youssef M, Younis M (2002) Energy aware TDMA based MAC for sensor network. In: IEEE workshop on integrated management of power aware communications computing and networking (IMPACCT'02), New York
8. Yang L, Elhanany I, Hairong Q (2005) An energy-efficient QoS-aware media access control protocol for wireless sensor networks. Mobile adhoc and sensor systems conference
9. Bharghavan V et al (1994) MACAW: a media access protocol for wireless LANS. Proc. ACM SIGCOMM. 24(4)
10. Younis O, Fahny S (2008) Distributed clustering in Ad-hoc sensor networks: a hybrid energy efficient approach, IEEE Transaction on Mobile Computing, 2004, pp 248–340