

# MAC Protocols for Wireless Sensor Networks: a Survey

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**Abstract**—Wireless sensor networks are appealing to researchers due to their wide range of application potential in areas such as target detection and tracking, environmental monitoring, industrial process monitoring, and tactical systems. However, lower sensing ranges result in dense networks, which bring the necessity to achieve an efficient medium access protocol subject to power constraints. Various MAC protocols with different objectives were proposed for wireless sensor networks. In this paper, we first outline the sensor network properties that are crucial for the design of MAC layer protocols. Then, we describe several MAC protocols proposed for sensor networks emphasizing their strengths and weaknesses. Finally, we point out open research issues on MAC layer design.

**Index Terms**—MAC Protocols, Sensor Networks, Survey

## I. INTRODUCTION

IMPROVEMENTS in hardware technology have resulted in low-cost sensor nodes which are composed of a single chip with embedded memory, processor, and transceiver. Low power capacities lead to limited coverage and communication range for sensor nodes compared to other mobile devices. Hence, for example in target tracking and border surveillance applications, sensor networks must include a large number of nodes, to cover the target area successfully.

Unlike other wireless networks, it is generally hard (or impractical) to charge/replace the exhausted battery, which gives way to the primary objective of maximizing node/network lifetime, leaving the other performance metrics as secondary objectives. Since the communication of sensor nodes will be more energy-consuming than their computation, it is a primary concern that the communication is minimized while achieving the desired network operation.

However, the medium access decision within a dense network composed of nodes with low duty-cycles is a hard problem that must be solved in an energy-efficient manner. Having these in mind, Section II emphasizes the peculiar features of sensor networks including reasons of potential energy wastes at medium access communication. Then, Section III gives brief definitions for the key MAC protocols proposed for sensor networks listing their advantages and disadvantages. Moreover, the protocols that propose the integration of MAC layer with other layers are

also investigated in Section III. Finally, Section IV concludes the survey on MAC protocols with a comparison of investigated protocols and provides a future direction to researchers for open issues that have not been studied thoroughly.

## II. MAC LAYER RELATED SENSOR NETWORK PROPERTIES

Maximizing the network lifetime is a common objective of sensor network research, since sensor nodes are assumed to be disposed when they are out of battery. Under these circumstances, the proposed MAC protocol must be energy-efficient by reducing the potential energy wastes presented in Section II.A. Types of communication patterns that are observed in sensor network applications should be investigated since these patterns are used to extract the behavior of the sensor network traffic that has to be handled by a given MAC protocol. Categorization of the possible communication patterns are outlined in Section II.B. Afterwards, the properties that must be possessed by a MAC protocol to suit a sensor network environment are presented in Section II.C.

### A. Reasons of Energy Waste

When a receiver node receives more than one packet at the same time, these packets are called “collided packets” even when they coincide partially. All packets that cause the *collision* have to be discarded and the re-transmissions of these packets are required which increase the energy consumption. Although some packets could be recovered by a *capture* effect, a number of requirements have to be achieved for its success. The second reason of energy waste is *overhearing*, meaning that a node receives packets that are destined to other nodes. The third energy waste occurs as a result of *control packet overhead*. Minimal number of control packets should be used to make a data transmission. One of the major sources of energy waste is *idle listening*, i.e., listening to an idle channel to receive possible traffic. The last reason for energy waste is *overemitting*, which is caused by the transmission of a message when the destination node is not ready. Given the facts above, a correctly-designed MAC protocol should prevent these energy wastes.

### B. Communication Patterns

Kulkarni *et al.* defines three types of communication patterns in wireless sensor networks [1]: *broadcast*, *convergecast*, and *local gossip*. *Broadcast* type of communication pattern is generally used by a base station (sink) to transmit some information to all sensor nodes of the network. Broadcasted information may include queries

of sensor query-processing architectures, program updates for sensor nodes, control packets for the whole system. The *broadcast* type communication pattern should not be confused with *broadcast* type packet. For the former, all nodes of the network are intended receivers whereas for the latter the intended receivers are the nodes within the communication range of the transmitting node.

In some scenarios, the sensors that detect an intruder communicate with each other locally. This kind of communication pattern is called *local gossip*, where a sensor sends a message to its neighboring nodes within a range. The sensors that detect the intruder, then, need to send what they perceive to the information center. That communication pattern is called *convergecast*, where a group of sensors communicate to a specific sensor. The destination node could be a clusterhead, data fusion center, base station.

In protocols that include clustering, clusterheads communicate with their members and thus the intended receivers may not be all neighbors of the clusterhead, but just a subset of the neighbors. To serve for such scenarios, we define a fourth type of communication pattern, *multicast*, where a sensor sends a message to a specific subset of sensors.

### C. Properties of a Well-defined MAC Protocol

To design a good MAC protocol for the wireless sensor networks, the following attributes must be considered [2]. The first attribute is the energy efficiency. We have to define energy efficient protocols in order to prolong the network lifetime.

Other important attributes are scalability and adaptability to changes. Changes in network size, node density and topology should be handled rapidly and effectively for a successful adaptation. Some of the reasons behind these network property changes are limited node lifetime, addition of new nodes to the network and varying interference which may alter the connectivity and hence the network topology. A good MAC protocol should gracefully accommodate such network changes. Other typical important attributes such as latency, throughput and bandwidth utilization may be secondary in sensor networks. Contrary to other wireless networks, fairness among sensor nodes is not usually a design goal, since all sensor nodes share a common task.

## III. PROPOSED MAC LAYER PROTOCOLS

In this section, a wide range of MAC protocols defined for sensor networks are described briefly by stating the essential behavior of the protocols wherever possible. Moreover, the advantages and disadvantages of these protocols are presented.

### 1) Sensor-MAC (S-MAC)

Locally managed synchronizations and periodic sleep-listen schedules based on these synchronizations form the basic idea behind the Sensor-MAC (S-MAC) protocol [2]. Neighboring nodes form virtual clusters to set up a common sleep schedule. If two neighboring nodes reside in two different virtual clusters, they wake up at listen periods of both clusters. A drawback of S-MAC algorithm is this possibility of following two different schedules, which

results in more energy consumption via idle listening and overhearing.

Schedule exchanges are accomplished by periodical SYNC packet broadcasts to immediate neighbors. The period for each node to send a SYNC packet is called the *synchronization period*. Figure 1 represents a sample *sender-receiver* communication. Collision avoidance is achieved by a carrier sense, which is represented as CS in the figure. Furthermore, RTS/CTS packet exchanges are used for unicast type data packets.

An important feature of S-MAC is the concept of message-passing where long messages are divided into frames and sent in a burst. With this technique, one may achieve energy savings by minimizing communication overhead at the expense of unfairness in medium access.

Periodic sleep may result in high latency especially for multi-hop routing algorithms, since all immediate nodes have their own sleep schedules. The latency caused by periodic sleeping is called *sleep delay* in [2]. Adaptive listening technique is proposed to improve the sleep delay, and thus the overall latency. In that technique, the node who overhears its neighbor's transmissions wakes up for a short time at the end of the transmission. Hence, if the node is the next-hop node, its neighbor could pass data immediately. The end of the transmissions is known by the *duration* field of RTS/CTS packets.

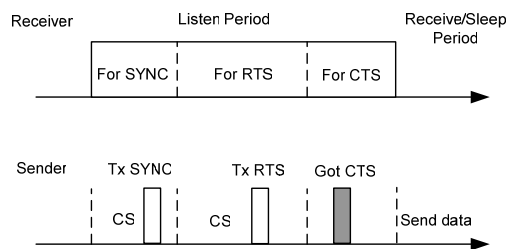


Figure 1. S-MAC Messaging Scenario [2]

*Advantages:* The energy waste caused by idle listening is reduced by sleep schedules. In addition to its implementation simplicity, time synchronization overhead may be prevented with sleep schedule announcements.

*Disadvantages:* Broadcast data packets do not use RTS/CTS which increases collision probability. Adaptive listening incurs overhearing or idle listening if the packet is not destined to the listening node. Sleep and listen periods are predefined and constant, which decreases the efficiency of the algorithm under variable traffic load.

### 2) WiseMAC

Spatial TDMA and CSMA with Preamble Sampling protocol is proposed in [3] where all sensor nodes are defined to have two communication channels. Data channel is accessed with TDMA method, whereas the control channel is accessed with CSMA method. Enz *et al.* proposed WiseMAC [4] protocol which is similar to Hoiydi *et al.*'s work [3] but requires only a single-channel. WiseMAC protocol uses non-persistent CSMA (np-CSMA) with preamble sampling as in [3] to decrease idle listening. In the preamble sampling technique, a preamble precedes



protocols.

*Disadvantages:* Transmission slots are set to be seven times longer than the random access period [5]. However, all nodes are defined to be either in receive or transmit states during the random access period for schedule exchanges. This means that without considering the transmissions and receptions, the duty cycle is at least 12.5 %, which is a considerably high value. For a time slot, every node calculates each of its two-hop neighbors' priorities on that slot. In addition, this calculation is repeated for each time slot, since the parameters of the calculation change with time.

#### 4) SIFT

Sift [7] is a MAC protocol proposed for event-driven sensor network environments. The motivation behind Sift is that when an event is sensed, the first  $R$  of  $N$  potential reports is the most crucial part of messaging and has to be relayed with low latency. Jamieson *et al.* use a non-uniform probability distribution function of picking a slot within the slotted contention window. If no node starts to transmit in the first slot of the window, then each node increases its transmission probability exponentially for the next slot assuming that the number of competing nodes is small.

In [7], Sift is compared with 802.11 MAC protocol and it is showed that Sift decreases latency considerably when there are many nodes trying to send a report. Since Sift is a method for contention slot assignment algorithm, it is proposed to co-exist with other MAC protocols like S-MAC. Based on the same idea, CSMA/p\* is proposed in [8] where p\* is a non-uniform probability distribution that optimally minimizes latency. However, Tay *et al.* state that Sift has a distribution approximate to CSMA/p\*.

*Advantages:* Very low latency is achieved with many traffic sources. Energy consumption is traded off for latency as indicated below. However, when the latency is an important parameter of the system, slightly increased energy consumption must be accepted. It could be tuned to incur less energy consumption. The high energy consumption is a result of the arguments indicated below.

*Disadvantages:* One of the main drawbacks is increased idle listening caused by listening to all slots before sending. The second drawback is increased overhearing. When there is an ongoing transmission, nodes must listen till the end in order to contend for the next transmission which causes overhearing. Besides, system-wide time synchronization is needed for slotted contention windows. That is why, the implementation complexity of Sift would be increased for the protocols not utilizing time synchronization.

#### 5) DMAC

Convergecast is the mostly observed communication pattern within sensor networks. These unidirectional paths from possible sources to the sink could be represented as data gathering trees. The principal aim of DMAC [9] is to achieve very low latency, but still to be energy efficient. DMAC could be summarized as an improved Slotted Aloha algorithm where slots are assigned to the sets of nodes based on a data gathering tree as shown in Figure 3. Hence, during the *receive* period of a node, all of its child nodes has

*transmit* periods and contend for the medium. Low latency is achieved by assigning subsequent slots to the nodes that are successive in the data transmission path.

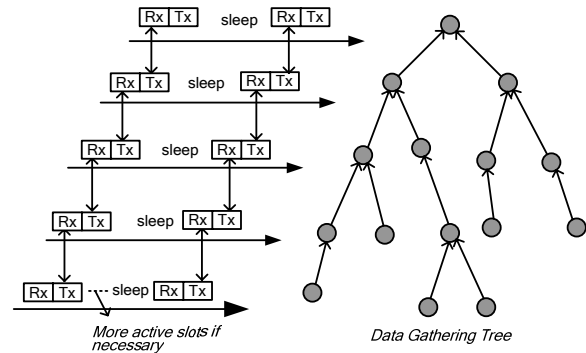


Fig. 3. A data gathering tree and its DMAC implementation [9]

*Advantages:* DMAC achieves very good latency compared to other sleep/listen period assignment methods. The latency of the network is crucial for certain scenarios, in which DMAC could be a strong candidate.

*Disadvantages:* Collision avoidance methods are not utilized, hence when a number of nodes that has the same schedule (same level in the tree) try to send to the same node, collisions will occur. This is a possible scenario in event-triggered sensor networks. Besides, the data transmission paths may not be known in advance, which precludes the formation of the data gathering tree.

#### 6) Timeout-MAC (T-MAC) / Dynamic Sensor-MAC (DSMAC)

Static sleep-listen periods of S-MAC result in high latency and lower throughput as indicated earlier. Timeout-MAC (T-MAC) [10] is proposed to enhance the poor results of S-MAC protocol under variable traffic load. In T-MAC, listen period ends when no activation event has occurred for a time threshold  $TA$ . The decision for  $TA$  is presented along with some solutions to the *early sleeping* problem defined in [10]. Variable load in sensor networks are expected, since the nodes that are closer to the sink must relay more traffic. Although T-MAC gives better results under these variable loads, the synchronization of the listen periods within virtual clusters is broken. This is one of the reasons for the *early sleeping* problem.

Dynamic Sensor-MAC (DSMAC) [11] adds dynamic duty cycle feature to S-MAC. The aim is to decrease the latency for delay-sensitive applications. Within the SYNC period, all nodes share their one-hop latency values (time between the reception of a packet into the queue and its transmission). All nodes start with the same duty cycle. Figure 4 conceptually depicts DSMAC duty cycle doubling. When a receiver node notices that average one-hop latency value is high, it decides to shorten its sleep time and announces it within SYNC period. Accordingly, after a sender node receives this sleep period decrement signal, it checks its queue for packets destined to that receiver node. If there is one, it decides to double its duty cycle when its battery level is above a specified threshold.

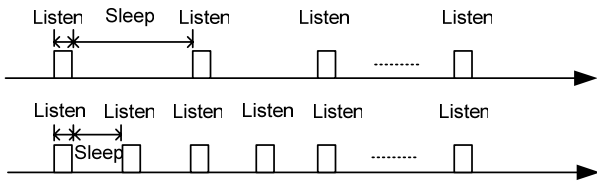


Fig 4. DSMAC duty cycle doubling [11]

The duty cycle is doubled so that the schedules of the neighbors will not be affected. The latency observed with DSMAC is better than the one observed with S-MAC. Moreover, it is also shown to have better average power consumption per packet.

#### 7) Integration of MAC with Other Layers

Limited research has been carried out to integrate different network layers to one layer or to benefit from the cross-layer interactions between *routing* and *MAC* layers for sensor networks. One such research is done by Safwat *et al.* who proposed two routing algorithms that favor the information about successful/unsuccessful CTS or ACK reception [12].

Cui *et al.* have research in that area with the objectives of MAC/Physical layer integration and Routing/MAC/Physical layer integration [13]. They propose a variable length TDMA scheme where the slot length is assigned according to some criteria for the optimum energy consumption in the network. Among these criteria, the most crucial ones are information about the traffic generated by each node and distances between each node pair. Based on these values, they formulate a Linear Programming (LP) problem where the decision variables are normalized time slot lengths between nodes. They solve this LP problem using an LP solver which returns the optimum number of time slots for each node pairs as well as the related routing decisions for the system.

The proposed solution could be quite beneficial for scenarios where the required data could be prepared. However, it is generally hard to have the node distance information and the traffic generated by the nodes. Besides, LP solver could only be run on a powerful node. However, the dynamic behaviors of sensor networks will require online decisions which are very costly to calculate and hard to adapt to an existing system.

Multihop Infrastructure Network Architecture (MINA) is another work for integrating MAC and routing protocols [14]. Ding *et al.* propose a layered multi-hop network architecture where the network nodes with the same hop-count to the base station are grouped into the same layer. Channel access is a TDMA-based MAC protocol combined with CDMA or FDMA. The super-frame is composed of a control packet, a beacon frame and a data transmission frame. Beacon and data frames are time slotted. In the clustered network architecture, all members of a cluster submit their transmission requests in beacon slots. Accordingly, the cluster-head announces the schedule of the data frame.

The routing protocol is a simple multi-hop protocol where each node has a forwarder node at one nearer layer to the base station. The forwarding node is chosen from candidates

based on the residual energies. Ding *et al.* then formulate the channel allocation problem as an NP-complete problem and propose a sub-optimal solution. Moreover, the transmission range of sensor nodes is a decision variable, since it affects the layering of the network (hop-counts change). Simulations are run to find a good range of values for a specific scenario.

The proposed system in [14] is a well-defined MAC/Routing system. However, the tuning of the range parameter is an important task which should be determined at the system initialization. In addition, all node-to-sink paths are defined at the startup and are defined to be static, since channel frequency assignments of nodes are done at the startup accordingly. This makes the system intolerant to failures.

Geographic Random Forwarding (GeRaF) is actually proposed as a routing protocol, but the underlying MAC algorithm is also defined in the work which is based on CSMA/CA [15]. That gives us not integrated but a complete solution for a sensor network's communication layers. The difficulty of the system proposed is its need for additional radio, which is used for busy tone announcement. Rugin *et al.* [16] and Zorzi *et al.* [15] improved GeRaF reducing it to a one-channel system. However, sensor nodes' and their neighbors' location information are needed for those protocols. Besides, the forwarding node is chosen among nodes that are awake at the time of the transmission request. That may result in more power consuming routing, and an increase in latency.

#### IV. OPEN ISSUES AND CONCLUSIONS

Table I represents a comparison of MAC protocols investigated. *Time Synchronization Needed* column indicates whether the protocol assumes that the time synchronization is achieved externally. *Adaptivity to Changes* means ability to handle topology changes.

The two S-MAC variants, namely, T-MAC and DSMAC, have the same features with S-MAC given in Table I. The cross-layer protocols include additional layers other than the MAC layer, and are not considered in this comparison.

TABLE I. COMPARISON OF MAC PROTOCOLS

	<i>Time Synch. Needed</i>	<i>Comm. Pattern Support</i>	<i>Type</i>	<i>Adaptivity to Changes</i>
<i>S-MAC / T-MAC / DSMAC</i>	No	All	CSMA	Good
<i>WiseMAC</i>	No	All	np-CSMA	Good
<i>TRAMA</i>	Yes	All	TDMA / CSMA	Good
<i>SIFT</i>	No	All	CSMA/CA	Good
<i>DMAC</i>	Yes	Convergecast	TDMA / Slotted Aloha	Weak

Although there are various MAC layer protocols proposed for sensor networks, there is no protocol accepted as a standard. One of the reasons behind this is the MAC protocol choice will, in general, be application-dependent, which means that there will not be *one* standard MAC for

sensor networks. Another reason is the lack of standardization at lower layers (physical layer) and the (physical) sensor hardware.

TDMA has a natural advantage of collision-free medium access. However, it includes clock drift problems and decreased throughput at low traffic loads due to idle slots. The difficulty with TDMA systems are the synchronization of the nodes and adaptation to topology changes where these changes are caused by insertion of new nodes, exhaustion of battery capacities, broken links because of interference, sleep schedules of relay nodes, scheduling caused by clustering algorithms. The slot assignments, therefore, should be done regarding such possibilities. However, it is not easy to change the slot assignment within a decentralized environment for traditional TDMA, since all nodes must agree on the slot assignments.

In parallel with the common networking lore, CSMA methods have a lower delay and promising throughput potential at lower traffic loads, which generally happens to be the case in wireless sensor networks. However, additional collision avoidance or collision detection methods should be employed to handle the collision possibilities.

FDMA is another scheme that offers a collision-free medium. Though, it brings an additional circuitry requirement to dynamically communicate with different radio channels. This increases the cost of the sensor nodes, which is contrary to the objective of the sensor network systems.

CDMA also offers collision-free medium, but its high computational requirement is a major obstacle for less energy consumption objective of the sensor networks. In pursuit of low computational cost requirements of wireless CDMA sensor networks, there has been limited effort to investigate source and modulation schemes, particular signature waveforms, designing simple receiver models, and other signal synchronization problems. If it is shown that the high computational complexity of CDMA could be traded with its collision avoidance feature, CDMA protocols could also be considered as candidate solutions for sensor networks. Lack of comparison of TDMA, CSMA or other medium access protocols in a common framework is a crucial deficiency of the literature.

Common wireless networking experience also suggests that link-level performance alone may provide misleading conclusions about the system performance. Similar conclusion can be drawn for upper layers as well. Hence, the more layers contributing to the decision, the more efficient the system can be. For instance, the routing path could be chosen depending on the collision information from the medium access layer. Moreover, layering of the network protocols creates overheads for each layer which causes more energy consumption for each packet. Therefore, integration of the layers is also a promising research area which has to be studied more extensively.

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