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, low sensing ranges result in dense networks and thus it becomes necessary to achieve an efficient medium-access protocol subject to power constraints. Various medium-access control (MAC) protocols with different objectives have been proposed for wireless sensor networks. In this article, 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 with regard to MAC layer design.

INTRODUCTION

Improvements in hardware technology have resulted in low-cost sensor nodes, which are composed of a single chip embedded with memory, a processor, and a 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 in order to cover the target area successfully.

Unlike other wireless networks, it is generally difficult or impractical to charge/replace exhausted batteries. That is why the primary objective in wireless sensor networks design is 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 to minimize communication while achieving the desired network operation.

However, the medium-access decision within a dense network composed of nodes with low duty-cycles is a challenging problem that must be solved in an energy-efficient manner. Keeping this in mind, we first emphasize the peculiar features of sensor networks, including reasons for potential energy waste at medium-access communication. Then we give brief definitions for the key medium-access control (MAC) protocols proposed for sensor networks, listing their advantages and disadvantages. Moreover, protocols that propose the integration of MAC layer with other layers are also investigated. Finally, the survey of MAC protocols is concluded with a comparison of investigated protocols and future directions are provided for researchers with regard to open issues that have not been studied thoroughly.

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 dead when they are out of battery. Under these circumstances, the proposed MAC protocol must be energy efficient by reducing the potential energy wastes presented below. The types of communication patterns that are observed in sensor network applications should be investigated, since these patterns determine the behavior of the sensor network traffic that has to be handled by a given MAC protocol. The categorization of possible communication patterns is outlined, and the necessary MAC-protocol properties suitable for a sensor network environment are presented.

REASONS OF ENERGY WASTE

When a node receives more than one packet at the same time, these packets are termed collided, even when they coincide only partially. All packets that cause the *collision* have to be discarded and retransmissions 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 successful recovery. The second reason for 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*. A minimal number of control packets should be used to make a data transmission. One of the major sources of energy waste is *idle listening*, that is, listening to an idle channel in order to receive possible traffic. The last reason for energy waste is *overemitting*, which is caused by the transmission of a message when the destination

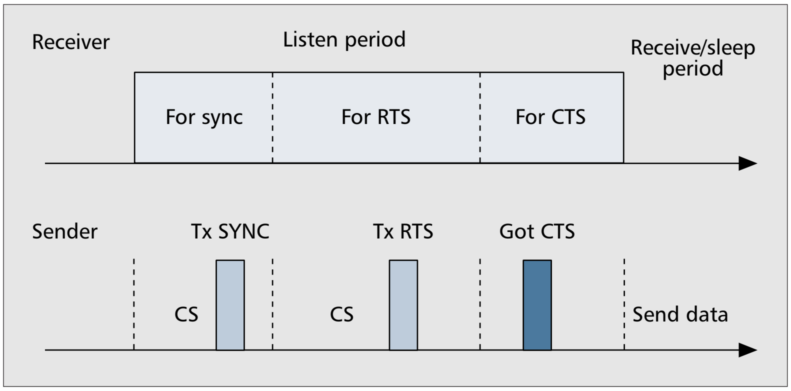


Figure 1. *The S-MAC messaging scenario [2].*

node is not ready. Given the above facts, a correctly designed MAC protocol should prevent these energy wastes.

COMMUNICATION PATTERNS

Kulkarni define three types of communication patterns in wireless sensor networks [1]: *broadcast*, *convergecast*, and *local gossip*. A broadcast pattern is generally used by a base station (sink) to transmit some information to all the sensor nodes of the network. Broadcasted information may include queries of sensor query-processing architectures, program updates for sensor nodes, or control packets for the whole system. The broadcast communication pattern should not be confused with broadcast packets. 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 event 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. After the sensors detect an event, they need to send what they perceive to the information center. That communication pattern is called *convergecast*, in which a group of sensors communicate to a specific sensor. The destination node could be a clusterhead, a data fusion center, or a 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 such scenarios, we define a fourth type of communication pattern — *multicast* — where a sensor sends a message to a specific subset of sensors.

PROPERTIES OF A WELL-DEFINED MAC PROTOCOL

To design a good MAC protocol for wireless sensor networks, the following attributes must be considered [2]. The first attribute is 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 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 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.

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.

SENSOR-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 so as to set up a common sleep schedule. If two neighboring nodes reside in two different virtual clusters, they wake up at the listen periods of both clusters. A drawback of the 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 periodic 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 (represented as CS in the figure). Furthermore, RTS/CTS packet exchanges are used for unicast-type data packets.

S-MAC also includes the concept of message passing, in which 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 multihop routing algorithms, since all intermediate nodes have their own sleep schedules. The latency caused by periodic sleeping is called *sleep delay* [2]. The adaptive listening technique is proposed to improve the sleep delay and thus the overall latency. In that technique, the node that 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 the RTS/CTS packets.

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 by 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.

WISEMAC

Hoiydi proposed the "Spatial TDMA and CSMA with Preamble Sampling" protocol in which all sensor nodes are defined to have two communication channels [3]. The data channel is accessed using TDMA, whereas the control channel is accessed by CSMA. The WiseMAC [4] protocol is similar to Hoiydi'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 each data packet for alerting the receiving node. All nodes in a network sample the medium with a common period, but their relative schedule offsets are independent. If a node finds the medium busy after it wakes up and samples the medium, it continues to listen until it receives a data packet or the medium becomes idle again. The size of the preamble is initially set to be equal to the sampling period.

However, the receiver may not be ready at the end of the preamble, due to factors such as interference, which causes the possibility of overemitting-type energy waste. Moreover, overemitting is increased with the length of the preamble and the data packet, since no handshake is done with the intended receiver.

To reduce the power consumption incurred by the predetermined fixed-length preamble, WiseMAC offers a method to dynamically determine the length of the preamble. That method uses the knowledge of the sleep schedules of the transmitter node's neighbors. The nodes learn and refresh their neighbor's sleep schedule during every data exchange as part of the Acknowledgment message. In that way, every node keeps a table of the sleep schedules of its neighbors. Based on the neighbors' sleep schedule tables, WiseMAC schedules transmissions so that the destination node's sampling time corresponds to the middle of the sender's preamble. To decrease the possibility of collisions caused by that specific start time of a wake-up preamble, a random wake-up preamble is advised.

Another parameter affecting the choice of the wake-up preamble length is the potential clock drift between the source and the destination. A lower bound for the preamble length is calculated as the minimum of destination's sampling period, T_w, and the potential clock drift with the destination, which is a multiple of the time since the last ACK packet arrived. Considering this lower bound, a preamble length (T_p) is chosen randomly. Figure 2 presents the WiseMAC concept.

Advantages — The simulation results show that WiseMAC performs better than one of the S-MAC variants [4]. Besides, its dynamic preamble length adjustment results in better performance under variable traffic conditions. In addition, clock drifts are handled in the protocol definition, which mitigates the external time synchronization requirement.

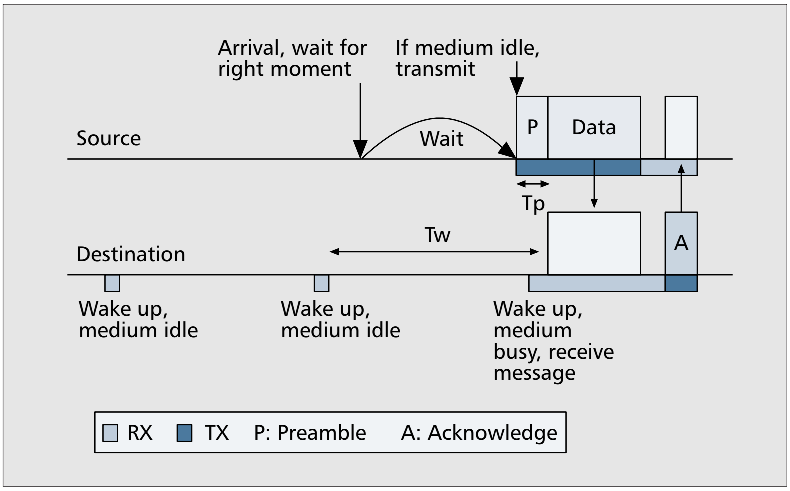


Figure 2. *The WiseMAC concept [4].*

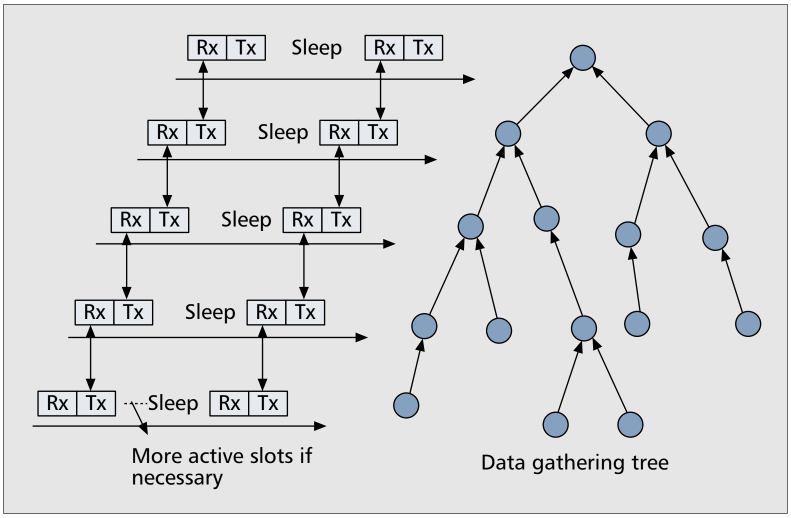
Disadvantages — The main drawback of WiseMAC is that decentralized sleep–listen scheduling results in different sleep and wake-up times for each neighbor of a node. This is an important problem especially for broadcast-type communication, since broadcasted packets will be buffered for neighbors in sleep mode and delivered many times as each neighbor wakes up. However, this redundant transmission will result in higher latency and power consumption.

In addition, the hidden terminal problem accompanies the WiseMAC model, as in the Spatial TDMA and the CSMA with Preamble Sampling algorithm. That is because WiseMAC is also based on nonpersistent CSMA. This problem will result in collisions when one node starts to transmit the preamble to a node that is already receiving another node's transmission where the preamble sender is not within range.

TRAFFIC-ADAPTIVE MAC PROTOCOL

TRAMA [5] is a TDMA-based algorithm proposed to increase the utilization of classical TDMA in an energy-efficient manner. It is similar to Node Activation Multiple Access (NAMA) [6], in which for each time slot a distributed election algorithm is used to select one transmitter within each two-hop neighborhood. This kind of election eliminates the hidden-terminal problem and hence ensures that all nodes in the one-hop neighborhood of the transmitter will receive data without any collision. However, NAMA is not energy efficient and incurs overhearing.

Time is divided into random-access and scheduled-access (transmission) periods. The random-access period is used to establish two-hop topology information and the channel access is contention-based within that period. A basic assumption is that, with the information passed by the application layer, the MAC layer can calculate the transmission duration needed, which is denoted as *SCHEDULE_INTERVAL*. Then, at time t, the node calculates the number



■ **Figure 3.** *A data gathering tree and its DMAC implementation [9].*

of slots for which it will have the highest priority among two-hop neighbors within the period [t, t+ *SCHEDULE_INTERVAL*]. The node announces the slots it will use as well as the intended receivers for these slots with a *schedule packet*. Additionally, the node announces the slots for which it has the highest priority but it will not use. The schedule packet indicates the intended receivers using a bitmap whose length is equal to the number of its neighbors. Bits correspond to one-hop neighbors ordered by their identities. Since the receivers of those messages have the exact list and identities of the one-hop neighbors, they find out the intended receiver. When the vacant slots are announced, potential senders are evaluated for reuse of those slots. Priority of a node on a slot is calculated with a hash function of node's and slot's identities.

Analytical models for the delay performances of TRAMA and NAMA protocols are also presented and supported by simulations [5]. Delays are found to be higher, as compared to those of contention-based protocols, due to a higher percentage of sleep times.

Advantages — Higher percentage of sleep time and less collision probability are achieved, as compared to CSMA-based protocols. Since the intended receivers are indicated by a bitmap, less communication is performed for the multicast and broadcast types of communication patterns, compared to other 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 percent, 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.

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 are the most crucial part of messaging and have to be relayed with low latency. Jamieson et al. use a nonuniform 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 was compared with the 802.11 MAC protocol and it was shown that Sift decreases latency considerably when there are many nodes trying to send a report. Since Sift is a contention slot assignment algorithm, it is proposed to coexist with other MAC protocols like S-MAC. Based on the same idea, CSMA/p* [8] is proposed where p* is a nonuniform probability distribution that optimally minimizes latency. However, Tay et al. state that the probability distribution function of Sift to pick a slot is approximate to CSMA/p*.

Advantages — Very low latency is achieved for 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. The Sift algorithm could be tuned to incur less energy consumption. 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 until the end in order to contend for the next transmission, which causes overhearing. Besides, systemwide time synchronization is needed for slotted contention windows. That is why the implementation complexity of Sift would be larger than protocols not utilizing time synchronization.

DMAC

Convergecast is the most frequent communication pattern observed within sensor networks. Unidirectional paths from sources to the sink could be represented as data-gathering trees. The principal aim of DMAC [9] is to achieve very low latency for convergecast communications, but still be energy efficient. DMAC could be summarized as an improved Slotted Aloha algorithm in which slots are assigned to the sets of nodes based on a data gathering tree, as shown in Fig. 3. Hence, during the *receive* period of a node, all of its child nodes have *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.

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 have the same schedule (the 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.

TIMEOUT-MAC/DYNAMIC SENSOR-MAC

The static sleep–listen periods of S-MAC result in high latency and lower throughput, as indicated above. Timeout-MAC (T-MAC) [10] is proposed to enhance the poor results of the S-MAC protocol under variable traffic loads. In T-MAC, the 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 loads in sensor networks are expected, since the nodes that are closer to the sink must relay more traffic and traffic may change over time. 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 a 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 (the 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 the average one-hop latency value is high, it decides to shorten its sleep time and announces it within the 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.

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

INTEGRATION OF MAC WITH OTHER LAYERS

Limited research has been carried out on integrating different network layers into one layer or to benefit from cross-layer interactions between routing and MAC layers for sensor networks. For instance, Safwat *et al*. proposed two routing algorithms that favor the information about successful/unsuccessful CTS or ACK reception [12].

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

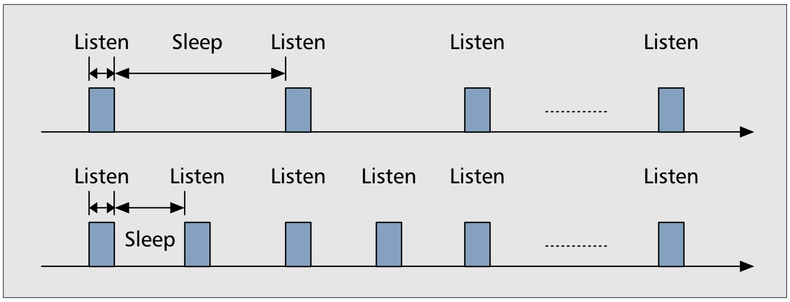


Figure 4. *DSMAC duty cycle doubling [11].*

The proposed solution could be beneficial in scenarios where the required data would be prepared. However, it is generally difficult to have the node-distance information and the traffic generated by the nodes. Besides, the LP solver can only be run on a powerful node. The dynamic behavior 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 method for integrating MAC and routing protocols [14]. Ding et al. proposed a layered multihop network architecture in which 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. The 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 multihop protocol where each node has a forwarder node at one nearer layer to the base station. The forwarding node was chosen from candidates based on the residual energies. Ding et al. then formulated the channel allocation problem as an NP-complete problem and proposed a suboptimal solution. Moreover, the transmission range of the sensor nodes is a decision variable, since it affects the layering of the network (the hop-counts change). Simulations were 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 that should be done at system initialization. In addi-

Variable loads in sensor networks are expected, since the nodes that are closer to the sink must relay more traffic and traffic may change over time. Although T-MAC gives better results under these variable loads, the synchronization of the listen periods within virtual clusters is broken.

	Time sync needed	Comm. pattern support	Type	Adaptivity to changes
S-MAC/T-MAC/DSMAC	No	All	CSMA	Good
WiseMAC	No	All	np-CSMA	Good
TRAMA	Yes	All	TDMA/CSMA	Good
Sift	No	All	CSMA/CA	Good
DMAC	Yes	Convergecast	TDMA/Slotted Aloha	Weak

Table 1. *Comparison of MAC protocols.*

tion, 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]. This work gives a complete (but not integrated) solution for a sensor network's communication layers. The difficulty of the system proposed is its need for an additional radio, which is used for the busy-tone announcement. Rugin et al. [16] and Zorzi [15] improved GeRaF by reducing it to a one-channel system. However, the sensor nodes' and their neighbors' location information is 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 routing with more power-consumption and an increase in latency.

Open Issues and Conclusions

Table 1 gives a comparison of the MAC protocols investigated. The column heading "Time Synchronization Needed" indicates whether the protocol assumes that the time synchronization is achieved externally and "Adaptivity to Changes" indicates the ability to handle topology changes.

The two S-MAC variants, namely, T-MAC and DSMAC, have the same features as S-MAC (Table 1). The cross-layer protocols include additional layers other than the MAC layer and are not considered in this comparison.

Although there are various MAC layer protocols proposed for sensor networks, there is no protocol accepted as a standard. One of the reasons for this is that 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 difficulties with TDMA systems are synchronization of the nodes and adaptation to topology changes when these changes are caused by insertion of new nodes, exhaustion of battery capacities, broken links due to interference, the sleep schedules of relay nodes, and scheduling caused by clustering algorithms. The slot assignments, therefore, should be done with regard to 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 accordance with 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.

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

CDMA also offers a collision-free medium, but its high computational requirement is a major obstacle for the less energy-consumption objective of sensor networks. In pursuit of low computational cost for wireless CDMA sensor networks, there has been limited effort to investigate source and modulation schemes, particularly 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-off against its collision-avoidance feature, CDMA protocols could also be considered as candidate solutions for sensor networks. Lack of comparisons 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. A similar conclusion can be drawn for the 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 that needs to be studied more extensively.

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Layering of the network protocols creates overheads for each layer, which causes more energy consumption for each packet. Therefore, integration of the layers is a promising research area that needs to be studied more extensively.