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Overview of Techniques for Improving MAC over Wireless Sensor Networks

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Abstract— In recent years, sensor networks have transitioned from being objects of academic research interest to a technology that is frequently being deployed in real-life applications and rapidly being commercialized. Wireless sensor networks use battery operated computing and sensing devices. Energy consumption continues to remain a barrier challenge in many sensor network applications that require long lifetimes. 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. This article surveys several techniques that show promise in addressing and alleviating this MAC improvement challenge. In this paper, we describe several MAC protocols proposed for sensor networks emphasizing their advantages and disadvantages. Finally, we point out conclusion on MAC layer design.

Index Terms— MAC Protocols, Sensor Networks, Survey, SMAC, duty cycle.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) enable new applications that involve a tight coupling between conventional computing infrastructure and the physical world. While the potential of sensor networks is only beginning to be realized, several challenges still remain. Arguably, the foremost among these is satisfying the requirement for long-lived operation (months to years) for several sensor network applications. Due to the limited capacity of batteries and the difficulty of frequent battery recharging or replacement, energy is a scarce and precious resource in sensor networks.

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.

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Having these in mind, Section II defines the peculiar features of sensor networks.

Then, Section III gives brief definitions of the proposed MAC protocols for sensor networks. 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

Improvements in hardware technology have resulted in low-cost sensor nodes which are composed of a single chip with embedded memory, processor, and transceiver. 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.

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 over emitting, 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, converge cast, 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.

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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 converge cast, where a group of sensors communicate to a specific sensor. The destination node could be a cluster head, data fusion center, base station. In protocols that include clustering, cluster heads communicate with their members and thus the intended receivers may not be all neighbors of the cluster head, 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.

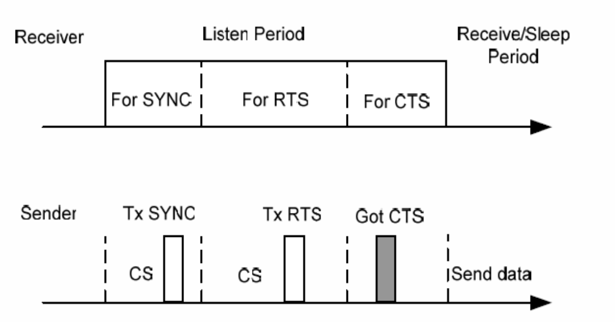

Fig 1. S-MAC Messaging Scenario

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.

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 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 reasons like interference, which causes the possibility of over emitting type energy waste.

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Moreover, over emitting 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 direct neighbors. The nodes learn and refresh their neighbor's sleep schedule during every data exchange as part of the acknowledgement message. In that way, every node keeps a table of sleep schedules of its neighbors. Based on neighbors' sleep schedule table, 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 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, Tw, and the potential clock drift with the destination which is a multiple of the time since the last ACK packet arrival. Considering this lower bound, a preamble length, Tp, is chosen randomly. Figure 2 presents the WiseMAC concept.

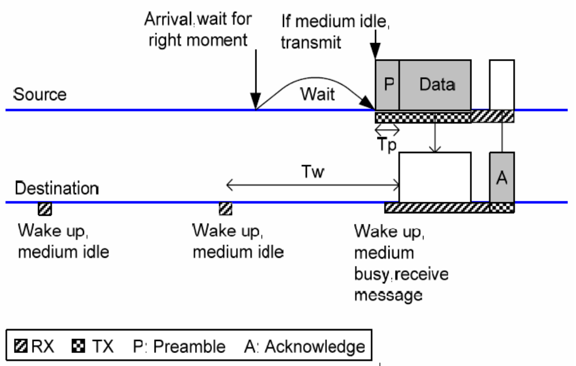

Fig 2. WiseMAC Concept

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.

Disadvantages: 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 especially an important problem for broadcast type of communication, since broadcasted packet 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 comes along with WiseMAC model as in the Spatial TDMA and CSMA with Preamble Sampling algorithm. That is because WiseMAC is also based on non-persistent 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 the range.

3) SIFT

Sift [5] 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 [5], 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 SMAC. Based on the same idea, CSMA/p* is proposed in [6] 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.

4) DMAC

Converge cast 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 [7] 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 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.

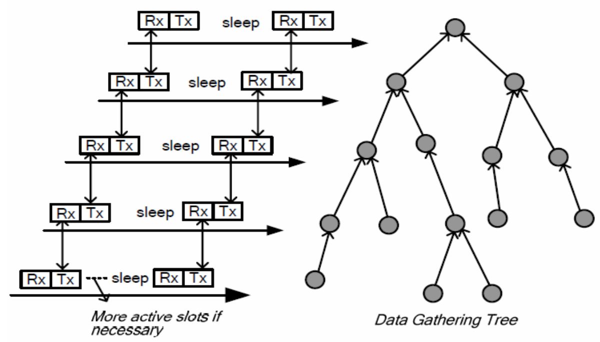

Fig 3. A data gathering tree and its DMAC implementation

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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.

5) 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) [8] 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 [8]. 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) 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.

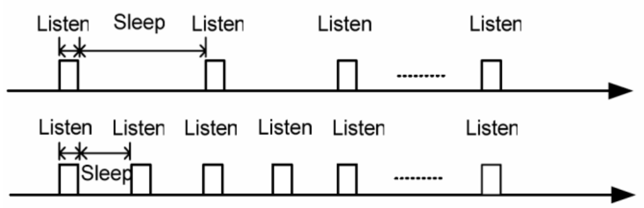

Fig 4. DSMAC duty cycle doubling

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.

6) Adaptive Duty Cycle SMAC

In order to adapt duty-cycle to traffic load, ADC-SMAC is proposed to improve SMAC. The modification over SMAC has two main aspects: various duty cycle schemes to provide different duty cycles to different nods, each node calculates its suitable duty cycle independently [9].

Similar to DSMAC, ADC- SMAC uses dynamic duty cycle schedule. Distinct from the subtle tuning of ADC-SMAC, DSMAC turns duty cycle by doubling or halving. So ADC-SMAC has advantages over DSMAC.

To reflect the different traffic loads, ADC-SMAC adopts utilization and average sleep delay of each node as the evaluation metric.

$U = (T_{rx} + T_{tx})/(T_{rx} + T_{tx} + T_{idle})$

Where, T_{rx} , T_{tx} , T_{idle} stands the total receiving time, the total transmission time, the total idle time.

The adjustment of duty cycle is done as mention hereby.

If $U > U_{high}$ and duty cycle < DC_{max} then

duty cycle = duty cycle + n %

else if $U > U_{low}$ and duty cycle < DC_{min} then

duty cycle = duty cycle – n%.

So the ADC-SMAC is proposed to find the balance between energy consumption and latency for different sensor network application in this paper. By this ADC-SMAC not only the total network energy consumption, but the end-to-end latency is significantly improved.

IV. FUTURE WORK AND CONCLUSIONS

Table I represents a comparison of MAC protocols. 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.

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 as listed below.

- 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

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.

Table 1. A data gathering tree and its DMAC implementation

	Time Synch. Needed	Comm. Pattern Support	Type	Adaptivity to Changes
S-MAC /T-MAC /DSMAC	No	All	CSMA	Good

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WiseMAC	No	All	np-CSMA	Good
SIFT	No	All	CSMA/CA	Good
DMAC	Yes	Converge cast	TDMA /Slotted Aloha	Weak

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.

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