A Survey on Schedule-Based MAC Protocols for Wireless Sensor Networks

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Abstract - In the last few years wireless sensor networks (WSN) have gained much research as well as commercial interest due to their wide range of application specially deployed in hazardous, hostile or remote areas. WSN-MAC protocols are generally classified as contention-based and schedule-based protocols. This paper discusses the properties of WSN-MAC protocols and the challenges of schedule-based MAC protocols. Then it surveys by describing several schedule-based MAC protocols for WSN which follows a comparison by emphasizing their strength and weaknesses with some other properties. Finally open research issues on MAC layer of WSN are also discussed.

Keywords - *Wireless Sensor Network (WSN), Medium Access Control, MAC Protocols, Scheduled based MAC Protocol, Energy Efficiency*

1. Introduction

Wireless sensor networks consist of a large number of resource constrained sensor nodes often deployed in inaccessible environments for different purposes such as event detection, periodic measurements, tracking, environment control, intelligent building and disaster relief operation etc. A basic sensor nodes comprises of a controller, memory, sensors and actuators, transceiver and power supply [1]. Generally the power supply requirement is fulfilled by embedding batteries with sensor nodes, and it is impractical to recharge/replace the exhausted batteries due to their inaccessible application areas. So designing an energy efficient communication protocol has become the main concern of the researchers, while depending on the application, other performance metric like: throughput, traffic adaptivity, scalability, fairness, delay and low overhead are also thoughtful.

Medium access control (MAC) is considered the most important technique for an energy efficient operation and to prolong the network lifetime. Current MAC protocols can be broadly divided into contention-based and schedule-based protocols. Contention-based protocols cause collision and overhearing problems which result in energy wastage. On the otherhand, schedule-based protocols results : low collision and low overhearing problems at the cost of some delays and low throughput. In this paper, we study some important schedule-based MAC protocols for WSN.

2. WSN-MAC Layer

This section discusses shortly about the properties of WSN-MAC layer, major source of energy wastage, categories of MAC protocol and schedule-based MAC protocol challenges.

2.1 MAC Layer Properties for WSN

In WSNs, because of sensor nodes, in a limited coverage area, a large number of sensor nodes are deployed in order to cover the target area successfully. The main objectives of the WSN-MAC layer is to create the sensor network infrastructure in order to establish the links between sensor nodes, when nodes access the shared wireless medium to send/receive to meet the certain application requirements. The most important performance required for MAC protocols are [2][3] high throughput, scalability, fairness, less delay, low overhead and energy efficiency. Among them for WSN-MAC protocol throughput, scalability, fairness and delay are the secondary requirements, while energy efficiency is the primary requirement. Owing to large number of sensor nodes in sensor network, it is impractical to change the sensor nodes battery frequently.

Users expect cost effective sensor network and hence demands a long lifetime of the sensor network. Therefore, the issue of energy conservation becomes important.

2.2 Major Source of Energy Wastes

A transceiver of a node in a WSN can be in one of the four operational states[4]: In the transmitting state only the transmit part of the transceiver is active with its associated antenna, similarly in the receiving state only the receive part is active. Both states consume almost same energy. The receiver in the idle state receives nothing but consumes significant energy. On the otherhand, in the sleep state, receiver consumes almost no energy, but results a deaf node.

The following situations cause major energy wastes[2] [5]:

i. **Collisions**: A transmitted packet may collide with other packet and may be discarded due to bad channel conditions and needs to be retransmitted, as a result costs and latency increases.
ii. **Overhearing**: When a node picks up packets for which it is not destined causes overhearing.
iii. **Idle Listening**: The receiver in the idle state (ready to receive) receives nothing but consumes significant energy.
iv. **Protocol Overhead**: For sending actual data, protocol may needs to send extra control frame like RTS, CTS, beacon signal, header, trailers which causes overhead and results extra energy consumptions.

2.3 Categories of WSN-MAC Protocol

The MAC protocols for WSNs are classified into two broad categories: i) Contention-based protocols and ii) Schedule-based protocols.

i. Contention-based protocols: These are based on Carrier Sense Multiple Access (CSMA) technique in which for a given transmit opportunity every neighbor node of the receiver can try its luck at the risk of collisions due to hidden terminal situations and costs higher for overhearing and idle listening also.

ii. Schedule-based protocols: These are based on TDMA technique. It can avoid collisions, overhearing and idle listening problems by time sharing the medium and resource access of the participants.

2.4 Scheduled based MAC Protocol Challenges

Although Schedule-based MAC protocols can avoid collisions, overhearing and idle listening problems, there have some drawbacks also [1]:

- During network setup and topology changes, the maintenance of scheduling involves traffic signalling which causes protocol overhead.
- A strict time synchronization between the neighboring nodes is required which involves some extra traffic signalling, and due to clock drift of oscillators and mobility of nodes, resynchronization is required.
- Schedule adaptation becomes difficult with the change of network traffic load.
- The nodes require significant amount of memory to keep its and its neighbors schedule.
- Distributed assignment of conflict free TDMA schedules is difficult[6].

So, the schedule-based MAC protocols are facing a challenge to minimize the problems stated above.

3. Discussion of the Schedule Based MAC Protocols

In this section, several schedule-based MAC protocols are examined on the basis of important characteristics of the protocols.

3.1 LEACH

LEACH(Low Energy Adaptive Clustering Hierarchy) [7] is a TDMA based protocol designed for dense sensor network. LEACH partitions the sensor nodes into clusters with a dedicated clusterhead in each cluster. Fig. 1 shows the cases.

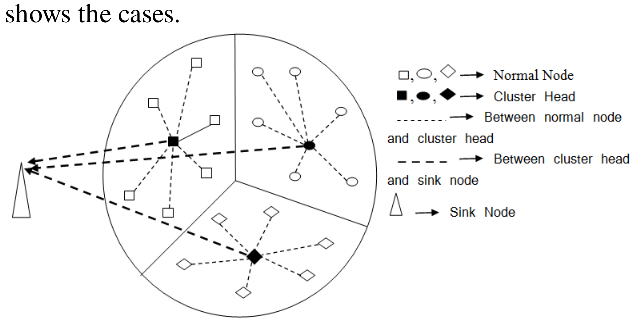

Fig. 1 Dynamic clusters of LEACH protocol. Nodes with same symbol belongs to same clusters

The role of the clusterhead is to create a TDMA schedule, distribute and maintain this schedule with its cluster members. The clusterhead aggregates data of its members and transmits data to the sink. The clusterhead selection is done by each nodes independently based on the last time the node served as a clusterhead[7]. The nonclusterhead choose their clusterhead based on the received signal strength. Since the clusterhead node is switched on all the time, so it burns its energy quickly and goes to die. This problem is solved by selecting the new clusterhead in next round. Fig. 2 shows a single round for LEACH protocol.

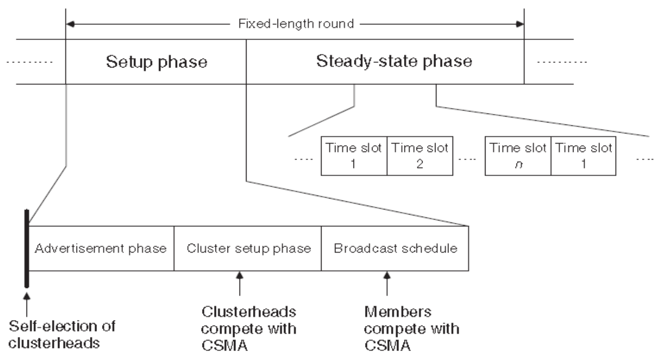

Fig. 2 Organization of LEACH rounds.

In LEACH, each round consists of a setup phase and a steady-state phase. During the setup phase, first nodes elect themselves as a clusterhead based on last serving. After that, in advertisement phase, clusterhead nodes inform their neighbors with an advertisement packet. The nonclusterhead nodes picks the packet with strongest received signal and inform the clusterhead node to join in the cluster during the cluster setup phase. Now, the clusterhead node knows all its member nodes and creates TDMA schedules with a randomly chosen CDMA code (for avoiding inter-cluster interference) for its members and then broadcast the schedule. Now the member nodes know their owned timeslot during which it has to be switched on. At a time the optimum percentage of clusterhead among all the nodes of the network is about 5%[7][8].

3.2 SMACS

The Self-Organizing Medium Access Control for Sensor Networks (SMACS)[9][10] protocol combines the detection of neighboring nodes and assignment of TDMA schedules. To set up exclusive links or channels to the nodes, SMACS depends on the following assumptions:

- Each node can tune its transceiver to an arbitrary channel among many available channels.
- All nodes divides its time locally into fixed-length superframes where superframes are subdivided into timeslots(but need not necessarily have the same phase as the neighbors superframes) and this requires time synchronization.
- Most of the nodes are stationary, such link or channel assignment is valid for long time.

In SMACS a link is directional, for bidirectional operation two such links are required. In SMACS neighbor discovery and link setup consist of four different cases which are shown in Fig. 3.

- Case 1: Node X, Y both so far unconnected
  - Node X sends invitation message
  - Node Y answers, telling X is unconnected to any other node
  - Node X tells Y to pick slot/frequency for the link
  - Node Y sends back the link specification
- Case 2: X has some neighbors, Y not
  - Node X will construct link specification and instruct Y to use it (since Y is unattached)
- Case 3: X no neighbors, Y has some
  - Y picks link specification
- Case 4: both nodes already have links
  - Nodes exchange their schedules and pick free slots/frequencies in mutual agreement.
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Message exchanges are protected by randomized back off.

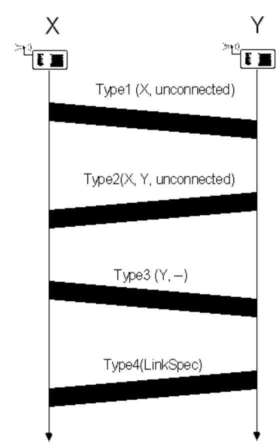

Fig. 3 SMACS link setup for two lonesome nodes.

After link setup the nodes wake up periodically (once per superframe) in the respective receiver time slots. The receiver is tuned to the corresponding channel.

3.3 TRAMA

The Traffic-Adaptive Medium Access (TRAMA)[11] protocol is introduced for energy-efficient collision-free channel access that allows nodes to create on demand schedule to access a single channel. It assumes that nodes are time synchronized and time is divided into cycles and each cycle consists of random access periods followed by a schedule access periods. TRAMA consists of three components: the Neighbor Protocol(NP), the Schedule Exchange Protocol(SEP), and the Adaptive Election Algorithm (AEA).

The Neighbor Protocol (NP) allows nodes to exchange two hop neighbor information by using randomly selected small timeslot in the random access phase. By the Schedule Exchange Protocol (SEP) a node transmits its current schedule to neighbor. It also allows to receive neighbors schedule by using random access phase. By using this neighbors schedule information, nodes decide which slots of scheduled access phase can be used. For this, each node calculates priority p for its node identifier x for each timeslot t using a global hash function h:

p(x,t)=h(x©t);

where (x©t) is the concatenation of x with current time t. Each node computes its own priority. The slots for which x has the highest priority value among all its two hop neighbors can be used by x to transmits its packets. The last winning slots is always used for broadcasting x's next schedule and x's neighbors should wakeup at this slot to receive x's next schedule. Possible conflicts arises when node D has the highest priority in B's two-hop neighborhood, and B knows it but on the otherhand node A has the highest priority in its two-hop neighborhood, so A think it can send (Fig. 4 shows the cases). The above problem is solved by Adaptive Election Algorithm(AEA) and also allow nodes to reuse their neighbor's unused winning slots.

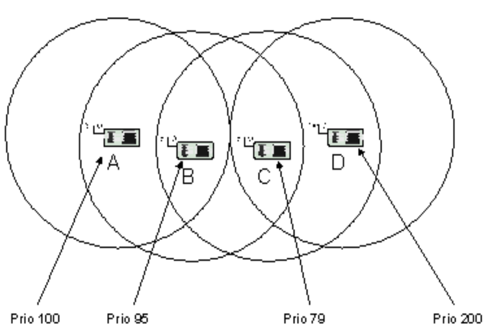

Fig. 4 TRAMA: Conflict situation.

3.4 EMACS

The EYES MAC(EMAC)[12] protocol is a TDMA based MAC protocol which improves the energy efficiency in exchange of some increase in latency. Here, time is divided into timeslot and each node allows to take control over a timeslot in a frame to transmit its data without having contend for the medium. Same timeslot can be used outside of the cell (directly connected nodes constitute a cell). Each node in the network maintains a table called schedule table in which it stores its cell's schedule and also the schedules of its neighbors.

In EMAC, a timeslot is further divided into three sections: Communication request (CR), Traffic Control (TC) and Data section (see Fig. 5).

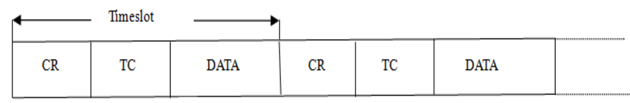

Fig. 5 EMACS Timeslot Structure

In the CR section other nodes can ask for data or to notify the availability of data for the timeslot controller node. Nodes that do not have a request during the current slot owner, will keep their transceiver on during the entire duration of the CR section. The owner of the slot always transmits its schedule for its data section and broadcast the schedule table in the TC section. When a timeslot is not owned by any node, all nodes will remain in sleep state during that timeslot. If a node is not addressed in the TC section, not its request was approved, the node will resume in the standby state during the entire duration of the data section. After the TC section the transmission of the actual data packet follows either uplink or downlink.

3.5 LMAC

Lightweight Medium Access Control Protocol(LMAC) [13] is a TDMA based self organizing (in terms of timeslot assignment and synchronization) MAC protocol developed with the intension to minimize the number of transceiver switches and to make the sleep interval adaptive to the amount of data traffic.

Each timeslot consists of a Control Message (CM) and Data Message (DM) period. During the network setup phase, to be synchronized, the gateway nodes take the initiative by controlling a timeslot. Using that timeslot the gateway nodes send a CM message (CM includes: Sender ID, Current Slot Number, Occupied Slots, Distance to Gateway, Collision in Slot, Destination ID, Data Size etc) to its one-hop neighbor. Then these neighbors synchronized their clocks with the gateway and pick a random timeslot to control (only this timeslot can be used for sending by this node but any other slots of its neighbors can be used for receiving), by a localized scheduling algorithm by assuring that same timeslot will not be used between the two hop neighbors for avoiding well known hidden terminal problem. Continue this process by sending CM to its next neighbors until all the nodes of the network get synchronized and occupy timeslot. After the network setup the data collection from the sensor nodes to the gateway nodes is efficiently done by using the Distance to Gateway field of the CM. Fig. 6 shows the cases.

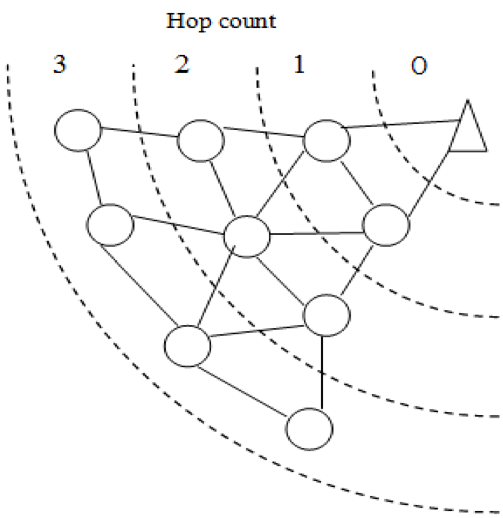

Fig.6 Nodes keep track of their hop distance to the closest gateway. This information is used for efficient routing to the gateway

3.6 AI-LMAC

An Adaptive, Information-Centric and Lightweight MAC(AI-LMAC)[14] is a TDMA based adaptive and information-aware version of LMAC protocol for WSN. Unlike LMAC which allows a node to own only single timeslot, whatever the data traffic will flow through that node, In AI-LMAC a node is allowed to own more timeslot depending on the amount of data traffic that will flow through it. So, this protocol provides fairness in the sense that bandwidth is allocated to the node depending on the data traffic it will encounter to flow.

AI-LMAC protocol maintains a parent child relationship with gateway. When a query is injected in the network through a gateway it uses Data Distribution Table (DDT) (every node maintains a DDT which records the data history for different query) to predict the amount of data their children will generate based on the current query and history. If a parent node realizes that a subset of immediate children are going to transmit large volume of data, it instructs the children for taking multiple slot (obviously on free basis between two-hop neighbor) under the current condition. Then, it is up to the child nodes to follow the advice as closely as possible.

AI-LMAC introduces two-dimensional fairness (Horizontal and Vertical) for i)minimizing the overall latency in the network and ii) for reducing the message buffering in the node and hence reduce network congestion. Fig.7 shows the cases.

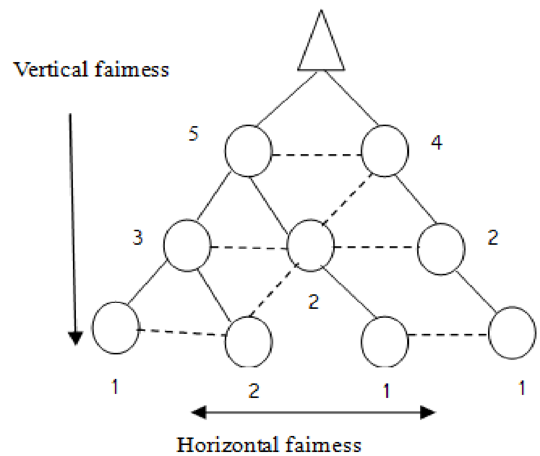

Fig. 7 Two-dimensional fairness in AILMAC: (i) Horizontal fairness divides bandwidth between siblings in accordance with requirement, and (ii) vertical fairness ensures that siblings don't get more bandwidth than their parent.

3.7 MC-LMAC

A Multi-Channel MAC Protocol (MC-LMAC)[15] for WSN are based on single channel LMAC protocol with the objective to increase the throughput by coordinating transmissions over multiple channels and hence increase the bandwidth utilization. Like LMAC, MC-LMAC also allows a node to take control over one timeslot per frame, but here the difference is the timeslot can be selected from multiple channel and the same timeslot can be selected over different channel between two-hop neighbor by assuring that same timeslot/channel pair not to be used within the two-hop neighborhood again by using localized scheduling algorithm.

In MC-LMAC the timeslot structure of LMAC is extended by adding a common frequency(CF) period which is accessed based on scheduling and divided into CF slots (the number of CF slot is equal to the number of channels and each slot is indexed by a channel number). Fig.8 shows the timeslot structure for MC-LMAC.

A sender controlling the current timeslot addresses the destination during the CF slot which is reserved for the channel number the sender controls. Receivers listen to the whole CF period. If a receiver is addressed during a CF slot it switches its transceiver with the senders associated frequency.

In Fig. 8, the numbers inside the circles represent the id's of the nodes. Assume that there are three frequencies F1, F2 and F3 and so, there are three CF slots. Sender 1 address node 4 on F1, sender 2 address node 5 on F2, sender 3 address node 6 on F3. In the control message (CM) and data section node 1 and 4 switch their transceiver on F1, node 2 and 5 on F2, node 3 and 6 on F3 and starts communicating at the same time on different frequency without interference which is impossible for single channel.

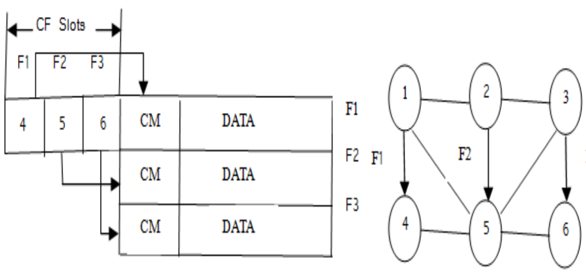

Fig. 8 MC-LMAC Timeslot structure and coordination scheme.

3.8 DMAC

DMAC[16] is an adaptive energy efficient low latency MAC protocol designed with the objective of data gathering with less delay for fixed nodes in WSN. Most of the active/sleep scheduled MAC protocols suffer from data forwarding interruption problem (DFI) by sleep delay. Because, all the nodes from source to sink on the multihop path are not notified about the ongoing transmission. Because of limited coverage area of a node, data forwarding process stops at the node whose next hop toward the sink is out of the overhearing range, hence results a significant latency. DMAC protocol addresses this issue and reduces interruption problems by allowing continuous packet forwarding. It also adaptively adjusts the duty cycle depending on the traffic load in the network.

In DMAC an interval is divided among sending, receiving and sleep period. Sending and receiving periods have the same length of μ. Depending on the depth d from a node to the sink node, a node advances its wake up schedule dμ from the sink schedule in data gathering tree. A node allows to send immediately after the receiving packets flow continuously from sensor nodes to the sink which reduces energy consumption and latency. Fig. 9 shows DMAC activity in data gathering tree.

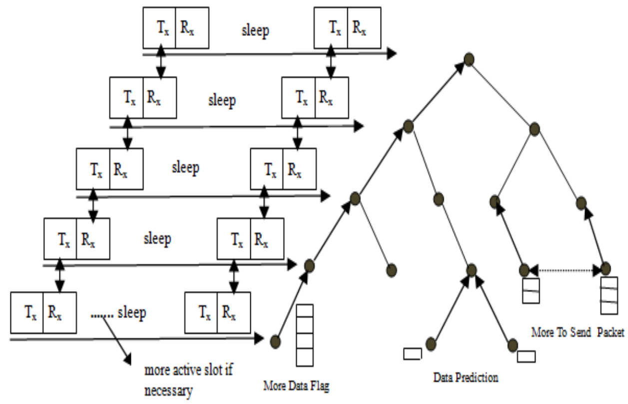

Fig. 9 DMAC in a data gathering tree

When a node has multiple packets to send, it needs to increase its and other hops' duty cycle on the multihop path. It is done by using more data flag in the MAC header and by data prediction process which allows next nodes to wake up one receiving slot time earlier. DMAC also utilizes more to send (MTS) packet when a node can not send packet for busy channel, a node send request MTS packet to its parent node in data gathering tree for waking up before its normal wake time.

3.9 DE-MAC

Distributed Energy-aware MAC(DE-MAC)[17] protocol for WSN is TDMA based protocol designed with the objective to prolong network lifetime by treating critical nodes (low power) differently in a distributed manner, i,e allow low power nodes to sleep more time than other nodes.

Initially, each node is assigned two timeslots for transmitting. If it has nothing to transmit it can sleep. Each node has also maintain a receive table, which is used by a node to know which slots its neighbors will use to transmit their packets and other nodes should listen during that slots.

Each node can be in any of the two phases: i)Normal operation phase and ii)Voting phase: when a node's current energy level falls below a threshold value from the previous winners energy level, it initiates a local election procedure in the voting phase to readjust their slots which is integrated with the normal TDMA slot assignment, so, DE-MAC protocol do not suffer from throughput loss.

The winners have twice the timeslots of the looser and it reduces the idle listening time of the critical low power nodes. Because, it can go to sleep mode if it has nothing to send during its own slot, thus saving energy and increasing the lifetime of the network.

Table 1: Comparison of Investigated Schedule Based WSN-MAC Protocols with advantage-disadvantage

Protocol	Advantages	Disadvantages
LEACH	• Localized coordination and control for cluster setup and operation enable scalability and robustness for dynamic network changes. • Local compression to reduce global communication. • Randomized rotation of the high-energy cluster-head among the various sensors leads to prolong the network lifetime.	• It assumes all the nodes in the network are homogeneous and energy constrained. i,e begin with same energy – but this assumption may not be realistic. • LEACH may encounter problem for large geographic areas, because a clusterhead may not have enough energy to reach the sink.
SMACS	• Can adapt to topology changes by repetition of neighbor discovery process. • Allows a mobile node to maintain connections to stationary nodes.	• If the superframe length is small then a timeslot for sending packets of a node may not enough, on the otherhand if its large then results high delay. • High dense low traffic load networks results quite often unnecessary nodes wake up. • For mobile nodes channel assignment is critical.
TRAMA	• Automatically adapt scheduling to traffic load. • If a slot is not used by any node, can be used by other node. • Nodes wake up only when they have data to send or receive. • It offers high channel utilization.	• Computational complexity is high. • Assume adequate synchronization among nodes. • It fails to address the issue of fairness.
EMACS	• This protocol allow nodes to determine their own schedule based on the requirements imposed by the service which increase power utilization. • This protocol offers scalability by dynamic configuration. • It also provides support for routing by providing some routing topology. • By grouping the sending and receiving, this protocol tries to minimize the number of transceiver transition and reduces power consumption.	• The protocol is not designed to provide high bandwidth utilization. • Nodes consume energy due to idle listening in the CR section.
LMAC	• Self organization of timeslot assignment and synchronization even when nodes are mobile reduces the protocol overhead. • Reduces the number of transceiver state switches to decrease the energy consumption and hence to increase the network lifetime.	• It sufferers from higher source to sink delay. • Lower bandwidth utilization. • Low throughput.
AI-LMAC	• It offers 2-Dimensional fairness by giving priority to a node, which is directly proportional to the amount of data a node expected to transmit to service an incoming query by using DDT. • It can adapts its operation depending on the requirements of the application, which results low latency.	• This protocol is application dependent. • All nodes need extra memory for data management framework.
MC-LMAC	• Provide high throughput. • Ensures an energy efficient operation. • High bandwidth utilization. • Low computational complexity.	• Multiple channels are required. Nodes to be equipped with multi channel supported transceiver.
DMAC	• Decreasing end to end delay using data gathering and prediction techniques. • Increasing throughput when traffic is high. • Solving data forwarding interruption problem.	• Does not provide reliability for end to end data delivery, so it can not be applied for real time application without improvement. • It does not take fairness into account.
DE-MAC	• Packet loss due to collision is absent because two nodes do not transmit in the same slot. • Slots are preassigned to each node, so no extra control overhead packets are required for contention.	• All nodes have to listen to all transmitted packets sending by other nodes, which results overhearing problem.

Table 2: Comparison of Investigated Schedule Based WSN-MAC Protocols with some performance metric

Protocol	Traffic adaptivity	Adaptivity to changes	Time Latency	Overhead	Complexity
LEACH	No	Moderate	High	Cluster election/ formation	Moderate
SMACS	No	Moderate	High	Neighborhood discovery, channel setup	Moderate
TRAMA	Yes	Good	High	Neighbor protocol, Schedule transmission	High
EMACS	No	Good	High	Timeslot selection and CR, TC of each time slot.	Low
LMAC	Yes	Moderate	High	Network setup and control message.	Low
AI-LMAC	Yes	Moderate	Low	Network setup, Control message and DDT	High
MC-LMAC	No	Good	Low	Network setup and Control information	Low
DMAC	Yes	Weak	Low	Synchronization, extra data flag in MAC header. idle listening during data predilection, MTS request /clear.	High
DE-MAC	No	Moderate	High	Local election process with TDMA slot assignment.	Moderate

4. Open Research Issues

Although schedule-based protocols have the advantage of energy conservation, because of the reduced duty cycle and less collision. But the scalability is not as good as that of a contention-based protocol because it is not easy to dynamically change its frame length and time slot assignments with the change of network topology.

Most of the protocols that we have surveyed in this paper are only evaluated through simulations, but to be confirmed about the performance and to avoid the unrealistic assumptions during simulations all these protocols needs to be implemented on actual sensor system. Most of the protocols are mainly concerned about energy efficiency not about the network security to protest against eavesdropping, to handle mobile nodes, QoS service support and real time data delivery for time critical application etc. These are also challenges for schedule-based WSN-MAC protocols.

Although some of the research work already have done on network security[18], nodes mobility[19], QoS service support[20] etc, still a lot of works have to be done for more efficient protocol in the areas mentioned above regarding the MAC layer of WSN.

5. Conclusion

In this paper, a survey of schedule–based MAC protocols in wireless sensor networks has been presented. The paper begins by introducing the properties of MAC layer followed by schedule-based protocol challenges. We have briefly described nine schedule-based MAC protocols. Finally, we have presented the merits and demerits of the protocols with other performance metrics. We expect that this survey will be useful to choose MAC protocol for satisfactory and efficient operation in specific application.

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