A SURVEY OF MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

Wireless sensor networks (WSNs) have become an active research area for the researchers. The sensor nodes are generally unattended after their deployment in hazardous, hostile or remote areas. These nodes have to work with their limited and non replenish able energy resources. Energy efficiency is one of the main design objectives for these sensor networks. In this paper, we present the challenges in the design of the energy efficient medium access control (MAC) protocols for the wireless sensor network. We describe several MAC protocols for the WSNs emphasizing their strength and weakness wherever possible. Finally, we discuss the future research directions in the MAC protocol design.

Keywords: Energy Efficiency, Medium Access Control, Wireless Sensor Network

1 INTRODUCTION

WIRELESS Sensor Networks (WSNs) have emerged as one of the dominant technology trends of this decade (2000-2010) that has potential usage in defence and scientific applications. These WSNs can be used for different purposes such as target tracking, intrusion detection, wildlife habitat monitoring, climate control and disaster management [1]. A typical node in the WSN consists of a sensor, embedded processor, moderate amount of memory and transmitter/receiver circuitry. These sensor nodes are normally battery powered and they coordinate among them selves to perform a common task.

These Wireless Sensor Networks have severe resource constrains and energy conservation is very essential. The sensor node's radio in the WSNs consumes a significant amount of energy. Substantial research has been done on the design of low power electronic devices in order to reduce energy consumption of these sensor nodes. Because of hardware limitations further energy efficiency can be achieved through the design of energy efficient communication protocols. Medium access control (MAC) is an important technique that ensures the successful operation of the network. One of the main functions of the MAC protocol is to avoid collisions from interfering nodes. The classical IEEE 802.11 MAC protocol for wireless local area network wastes a lot of energy because of idle listening. Designing power efficient MAC protocol is one of the ways to prolong the life time of the network. In this work we carried the study of the energy efficient MAC protocols for the wireless sensor network.

The rest of the paper is organized as follows. Section 2 discusses challenges in the design of the MAC protocol. Section 3 presents the different proposed MAC protocols emphasizing their strength and weakness wherever possible. Section 4 discusses future research directions in the MAC protocol design. Finally, Section 5 concludes the paper.

2 MAC PROTOCOL DESIGN CHALLENGES

The medium access control protocols for the wireless sensor network have to achieve two objectives. The first objective is the creation of the sensor network infrastructure. A large number of sensor nodes are deployed and the MAC scheme must establish the communication link between the sensor nodes. The second objective is to share the communication medium fairly and efficiently.

2.1 Attributes of a Good MAC Protocol

To design a good MAC protocol for the wireless sensor networks, the following attributes are to be considered [2].

(i) Energy Efficiency: The first is the energy efficiency. The sensor nodes are battery powered and it is often very difficult to change or recharge batteries for these sensor nodes. Sometimes it is beneficial to replace the sensor node rather than recharging them.

(ii) Latency: The second is latency. Latency requirement basically depends on the application. In the sensor network applications, the detected events must be reported to the sink node in real time so that the appropriate action could be taken immediately.

(iii) Throughput: Throughput requirement also varies with different applications. Some of the sensor network application requires to sample the information with fine temporal resolution. In such sensor applications it is better that sink node receives more data.

(iv) Fairness: In many sensor network applications when bandwidth is limited, it is necessary to ensure that the sink node receives information from all sensor nodes fairly. However among all of the above aspects the energy efficiency and throughput are the major aspects. Energy efficiency can be increased by minimizing the energy wastage.

2.2 Major Sources of Energy Wastes

Major sources of energy waste in wireless sensor network are basically of four types [2] [3].

(i) Collision: The first one is the collision. When a transmitted packet is corrupted due to interference, it has to be discarded and the follow on retransmissions increase energy consumption. Collision increases latency also.

(ii) Overhearing: The second is overhearing, meaning that a node picks up packets that are destined to other nodes.

(iii) Packet Overhead: The third source is control packet overhead. Sending and receiving control packets consumes energy too and less useful data packets can be transmitted.

(iv) Idle listening: The last major source of inefficiency is idle listening i.e., listening to receive possible traffic that is not sent. This is especially true in many sensor network applications. If nothing is sensed, the sensor node will be in idle state for most of the time. The main goal of any MAC protocol for sensor network is to minimize the energy waste due to idle listening, overhearing and collision.

2.3 MAC Performance Matrices

In order to evaluate and compare the performance of energy conscious MAC protocols, the following matrices are being used by the research community.

(i) Energy Consumption per bit: - The energy efficiency of the sensor nodes can be defined as the total energy consumed / total bits transmitted. The unit of energy efficiency is joules/bit. The lesser the number, the better is the efficiency of a protocol in transmitting the information in the network. This performance matrices gets affected by all the major sources of energy waste in wireless sensor network such as idle listening, collisions, control packet overhead and overhearing.

(ii) Average Delivery Ratio: - The average packet delivery ratio is the number of packets received to the number of packets sent averaged over all the nodes.

(iii) Average Packet Latency: - The average packet latency is the average time taken by the packets to reach to the sink node.

(iv) Network Throughput:-The network throughput is defined as the total number of packets delivered at the sink node per time unit.

3 PROPOSED MAC PROTOCOLS

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

The schedule based protocol can avoid collisions, overhearing and idle listening by scheduling transmit & listen periods but have strict time synchronization requirements. The contention based protocols on the other hand relax time synchronization requirements and can easily adjust to the topology changes as some new nodes may join and others may die few years after deployment. These protocols are based on Carrier Sense Multiple Access (CSMA) technique and have higher costs for message collisions, overhearing and idle listening.

3.1 IEEE 802.11

The IEEE 802.11 [19] is a well known contention based medium access control protocol which uses carrier sensing and randomized back-offs to avoid collisions of the data packets. The Power Save Mode (PSM) of the IEEE 802.11 protocol reduces the idle listening by periodically entering into the sleep state. This PSM mode is for the single-hop network where the time synchronization is simple and may not be suitable for multi-hop networks because of the problems in clock synchronization, neighbour discovery and network partitioning.

3.2 PAMAS: Power Aware Multi-Access Signaling

PAMAS: Power Aware Multi-Access [15] is one of the earliest contention based MAC protocol designed with energy efficiency as the main objective. In this protocol nodes which are not transmitting or receiving are turned "OFF" in order to conserve energy. This protocol uses two separate channels for the data and control packets. It requires the use of two radios in the different frequency bands at each sensor node leading to the increase in the sensors cost, size and design complexity. Moreover, there is significant power consumption because of excessive switching between sleep and wakeup states.

3.3 Sensor S-MAC

Sensor S-MAC [2] a contention based MAC protocol is modification of IEEE 802.11 protocol specially designed for the wireless sensor network in 2002. In this medium access control protocol sensor node periodically goes to the fixed listen/sleep cycle. A time frame in S-MAC is divided into to parts: one for a listening session and the other for a sleeping session. Only for a listen period, sensor nodes are able to communicate with other nodes and send some control packets such as SYNC, RTS (Request to Send), CTS (Clear to Send) and ACK (Acknowledgement). By a SYNC packet exchange all neighbouring nodes can synchronize together and using RTS/CTS exchange the two nodes can communicate with each other. The basic S-MAC scheme where node 1 transmits data to node 2 is shown in Fig. 1. A lot of energy is still wasted in this protocol during listen period as the sensor will be awake even if there is no reception/transmission.
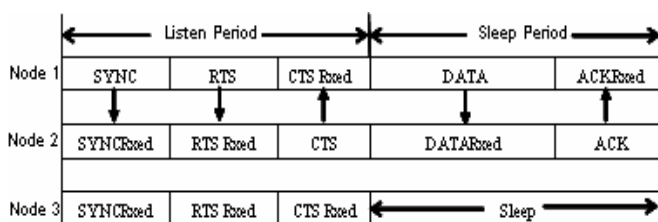

Figure 1: Basic S-MAC Scheme, Node 1 Transmits Data to Node 2

3.4 Timeout T-MAC

Timeout T-MAC [3] is the protocol based on the S-MAC protocol in which the Active period is pre-empted and the sensor goes to the sleep period if no activation event has occurred for a time 'Ta' as shown in Fig. 2. The event can be reception of data, start of listen/sleep frame time etc. The time 'Ta' is the minimal amount of idle listening per frame. The interval Ta > Tci + Trt + Tta + Tct where Tci is the length of the contention interval, Trt is the length of an RTS packet, Tta is the turn-around time (time between the end of the RTS packet and the beginning of the CTS packet) and Tct is the length of the CTS packet. The energy consumption in the Timeout T-MAC protocol is less than the Sensor S-MAC protocol. But the Timeout T-MAC protocol has high latency as compared to the S-MAC protocol.
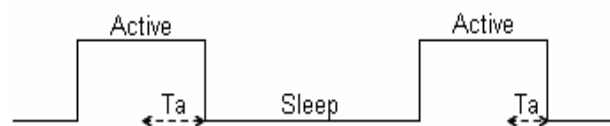

Figure 2: Basic T-MAC Scheme

3.5 Optimized MAC

In the Optimized MAC protocol [5], the sensors duty cycle is changed based on the network load. If the traffic is more than the duty cycle will be more and for low traffic the duty cycle will be less. The network load is identified based on the number of messages in the queue pending at a particular sensor. The control packet overhead is minimized by reducing the number and size of the control packets as compared to those used in the S-MAC protocol. This protocol may be suited for applications in which apart from energy efficiency there is need for low latency.

3.6 Traffic Adaptive Medium Access Protocol (TRAMA)

The traffic adaptive medium access (TRAMA) [6] is a TDMA based protocol that has been designed for energy efficient collision free channel in WSNs. In this protocol the power consumption has been reduced by ensuring collision free transmission and by switching the nodes to low power idle state when they are not transmitting or receiving. This protocol consists of three main parts: a) The Neighbor Protocol is for collecting the information about the neighboring nodes b) The Schedule Exchange Protocol is for exchanging the two-hop neighbor information and their schedule c) The Adaptive Election Algorithm decides the transmitting and receiving nodes for the current time slot using the neighborhood and schedule information. The other nodes in the same time slot are switched to low power mode.

The TRAMA is shown to be more energy efficient and has higher throughput than Sensor S-MAC protocol. However, the latency of TRAMA is more as compared to the other contention based MAC protocol such as S-MAC and IEEE 802.11. The delay performance obtained by the analytical model for TRAMA and NAMA [7] shows that TRAMA has higher delays than NAMA. This protocol may be suitable for applications which are not delay sensitive but require higher energy efficiency and throughput.

3.7 Self Organizing Medium Access Control for Sensor Networks (SMACS)

SMACS [9] is a schedule based medium access control protocol for the wireless sensor network. This MAC protocol uses a combination of TDMA and FDMA or CDMA for accessing the channel. In this protocol the time slots are wasted if the sensor node does not have data to be sent to the intended receivers. This is one of the drawbacks of this MAC scheme.

3.8 Aloha with Preamble Sampling

Aloha with Preamble Sampling is proposed in [11] where the ALOHA protocol [20] has been combined with the preamble sampling technique. The main draw back of the Carrier Sense Multiple Access (CSMA) is the energy wastage due to idle listening. El-Hoiydi in [11] proposed low power listening technique that efficiently duty cycles the radio (i.e., turns it ON periodically).This approach works at the physical layer based on the PHY Header going to sensor's radio. The Header starts with the Preamble which intimates the receiver of upcoming messages. The receiver periodically turns radio ON to sample for the incoming messages and if the preamble is detected, it continues listening for the normal message transfer. If the preamble is not detected it turns OFF radio till next sample. This carrier sensing approach as shown in Fig. 3 was combined with ALOHA by El-Hoiydi in [11] and named it Aloha with Preamble Sampling which is suitable for low traffic wireless sensor network applications. This paper also presents the power consumption, delay performance and life time computed by analytical methods.
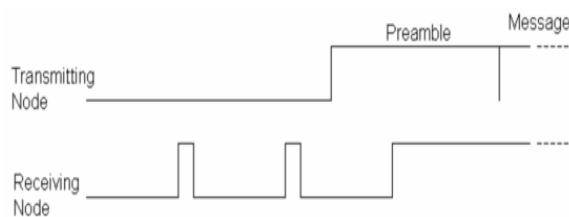
Figure 3: Low Power Listening and Preamble Sampling

3.9 WiseMAC

The WiseMAC [14] medium access control protocol was developed for the "WiseNET" wireless sensor network. This protocol is similar to Spatial TDMA and CSMA with Preamble Sampling protocol [13] where all the sensor nodes have two communication channels. TDMA is used for accessing data channel and CSMA is used for accessing control channel. However, WiseMAC [14] needs only one channel and uses non-persistent CSMA with preamble sampling technique to reduce power consumption during idle listening. This protocol uses the preamble of minimum size based on the information of the sampling schedule of its direct neighbors. The sleep schedules of the neighboring nodes are updated by the acknowledgement message (ACK) during every data transfer. WiseMAC is adaptive to the traffic loads and provides low power consumption during low traffic and high energy efficiency during high traffic. The simulation results show that WiseMAC performs better than S-MAC protocol.

3.10 Berkeley a Access Control (B-MAC)

The Berkeley Media Access Control (B-MAC) [10] is a contention based MAC protocol for WSNs. B-MAC is similar to Aloha with Preamble Sampling [11], which duty cycles the radio transceiver i.e. the sensor node turns ON/OFF repeatedly without missing the data packets. However in B-MAC, the preamble length is provided as parameter to the upper layer. This provides optimal trade-off between energy savings and latency or throughput. The paper also presents an analytical model for monitoring application to calculate and set B-MAC parameters in order to optimize the power consumption. The experimental results show B-MAC has better performance in terms of latency, throughput and often energy consumption as compared to S-MAC.

3.11 Energy Aware TDMA Based MAC

Energy Aware TDMA Based MAC [16] protocol assumes the formation of clusters in the network. Each of the cluster sensor nodes is managed by the Gateway. The Gateways collects the information from the other sensor nodes within its cluster, performs the data fusion, communicates with the other gateways and finally sends the data to the control center. The assignment of the time slots to the sensor nodes within its cluster is performed by Gateways. The Gateways inform to the other nodes about the time slot when it should listen to other nodes and the time slot when it can transmit own data.

This TDMA based MAC protocol consist of four main phases: data transfer, refresh, event triggered-

rerouting and refresh-based rerouting. The *data transfer phase* is for sending the data in its allocated time slot. During *refresh phase*, the nodes update its state (energy level, state, position etc) to the gateway. The gateway requires this nodes state information for performing rerouting during *event triggered-rerouting*. The *refresh-based rerouting* occurs periodically after the refresh phase. During both these rerouting phases the gateway execute the routing algorithms and sends new routes to the sensor nodes.

The paper presents two approaches for slot assignment based on graph parsing strategy: Breadth First Search (BFS) and Depth First Search (DFS). BFS technique, assigns the time slot numbers starting from outer most sensor node giving them contiguous slots. While DFS technique assigns contiguous time slots for the nodes on the route from outermost sensor node to the gateway.

Simulations have been performed for energy consumption per packet, end-to-end delay, throughput, nodes lifetime etc. against the buffer size for both BFS and DFS techniques. BFS saves the energy consumption in switching between the ON & OFF states and therefore the nodes lifetime is high. This technique requires the nodes to have sufficient buffer capacity. While DFS does not save the energy consumption of switching between the ON & OFF states but avoids buffer overflow problem. However, DFS has low latency and high throughput as compared to BFS.

3.12 Data Gathering MAC (D-MAC)

The Data–Gathering Medium Access Control (D-MAC) [12] is a schedule based MAC protocol which has been designed and optimized for tree based data gathering (converge cast communication) in wireless sensor network. The main objective of this MAC protocol is to achieve low latency and still maintaining the energy efficiency. In this protocol the time is divided in small slots and runs carrier sensing multiple access (CSMA) with acknowledgement within each slot to transmit/receive one packet. The sensor node periodically executes the basic sequence of '1' transmit, '1' receive and 'n' sleep slots. In this approach a single packet from a source node at depth 'k' in the tree reaches the sink node with a delay of just 'k' time slots. This delay is very small and it is in the order of tens of milliseconds. A data gathering (converge cast) tree with staggered DMAC slots is shown in Fig. 4.

D-MAC includes an overflow mechanism to handle the problem when each single source node has low traffic rate but the aggregate rate at intermediate node is larger than the basic duty cycle. In this mechanism the sensor node will remain awake for one extra time slot after forwarding the packet.
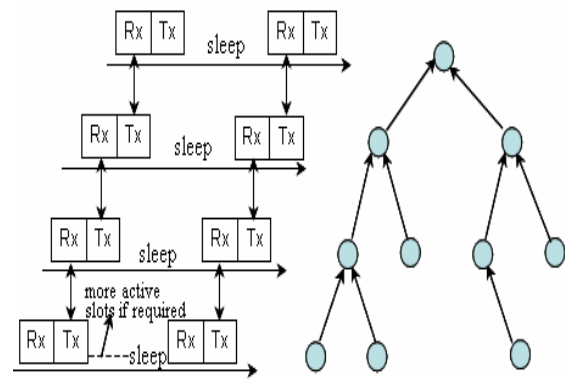
Figure 4: Data gathering tree in D-MAC scheme

Therefore, if two children were contending for parents receive slot, the loosing child will get a second chance to send its packet. The D-MAC uses a separate control packet named MTS (More to Send) to solve the problem of the interference between nodes on the different branches of the tree. The MTS packet makes all the nodes on the multi-hop path to remain active in case of nodes failure due to interference.

The simulation results shows that the D-MAC protocol outperforms the Sensor S-MAC protocol in terms of energy efficiency, latency and throughput in both multi-hop chain topology and random data gathering tree topology.

4   FUTURE RESEARCH DIRECTIONS

In the recent years a large number of medium access control (MAC) protocols for the wireless sensor network have been published by the researchers. Most of the work on the MAC focuses primarily on the energy efficiency in the sensor network [8]. However, still a lot of work has to done in the other areas at the MAC layer such as:

(i) Network Security: - Sensor network security at MAC layer to protect against eavesdropping and malicious behavior has to be studied further. Karlof et al. in TinySec [22] have proposed secure MAC protocol based on shared key but still more advanced schemes needs to be developed.

(ii) Nodes Mobility: - The nodes in the wireless sensor network were originally assumed to be static. Recently there has been increasing interest in medical care and disaster response applications where the mobile sensors can be attached to the patient, doctor or first responder. The mobility at the MAC layer has been considered in MMAC [21], still there is a lot of scope for future research in this area.

(iii) Evaluation on Sensor Platforms: - Most of the protocols for the wireless sensor network have been evaluated through the simulations. However, the performance of the MAC protocol needs to be evaluated on the actual sensor system. The researchers should focus on experimenting on the real sensor platforms.

(iv) Real Time Systems: - Energy efficiency is the main design objective of the sensor network but the reliable delivery of data in the real time is essential for certain time critical applications. This is also a promising research area which needs to be studied more extensively.

5 CONCLUSIONS

Recently several medium access control protocols for the wireless sensor network have been proposed by the researchers. However, no protocol is accepted as standard. This is because the MAC protocol in general will be application specific. Therefore, there will not be one standard MAC protocol for the WSNs.

The schedule based (TDMA) have collision free access to the medium but the synchronization is critical. Moreover, there is difficulty in adapting to the changes in the network topology because of the addition and deletion of nodes.

The contention based (CSMA) have low latency and high throughput. However, it still suffers from the collisions.

The Frequency Division Multiple Access (FDMA) scheme also allow collision free access to the media but the extra circuitry required to dynamically communicate with different radio channels increases the cost of the sensor nodes. This contradicts the main objective of the wireless sensor networks (WSNs).

The Code Division Multiple Access (CDMA) scheme also offers collision free access to the medium. However, the high computational complexity is the limitation in the lower energy consumption needs of the sensor network.

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