Comparative Study of Various Mac Protocols for Wireless Sensor Networks

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ABSTRACT
The wireless sensor network (WSN) was primarily developed as a military application to survey a battlefield. However, now a WSN is commonly used in many other industrial and commercial applications to monitor environmental conditions, health care applications and traffic controls. There are many different kinds of wireless sensor networks, however; they all normally come equipped with a radio transceiver or a wireless communication device or a power source. In this paper, we describe several MAC protocols proposed for sensor networks emphasizing their strengths and weaknesses.

General Terms
MAC Protocols.

Keywords
Wireless sensor networks, Mac protocols

1. INTRODUCTION
Wireless sensor network (WSN) is the combination of sensor, microelectronic and net communication technologies, which are widely applied in military, industry, environment monitoring, medical treatment and so on. Due to low power support for sensor nodes, energy efficiency becomes one of the core problems. From analysis of the sensor nodes, the communication module is the part which consumes most of the energy, which is the main optimization goal. The Medium Access Control (MAC) protocol directly controls the communication module, so it has important effect on the node's energy consumption. The major sources of energy inefficiency in WSN are collision, overhearing, idle listening, and control packet overheads. According to the four sources of energy waste, researchers have proposed different types of MAC protocols to improve energy consumptions so that the WSN can have a long lifetime. In this paper, we investigate the typical MAC protocols proposed in recent years. The remainder of this paper is structured as follows. Section II presents MAC protocols from four perspectives: contention-based, TDMA-based, hybrid, and cross layer MAC. Section III concludes the paper.

2. ENERGY EFFICIENT MAC PROTOCOLS FOR WSN
In this section, a wide range of MAC protocols mainly focused on energy efficiency described briefly by stating the essential behaviour of the protocols wherever possible. We categorize these MAC protocols into four classes.

2.1 Contention-based MAC

The contention-based MAC protocols must handle the possible collisions while data transmission. Obviously, a collision occurs when two or more nodes transmit their data. Simultaneously and interfere with each other. Contention based MAC protocols may deal with it through some contention resolution scheme such as retransmitting the data later or occupying the shared medium before data transmission. Compared with schedule-based MAC protocols, contention-based MAC protocols consume more energy because they waste energy in collisions and idle listening. Moreover, they do not give delay guarantees. However, they are very flexible and can handle the traffic fluctuations in wireless sensor networks. We describe some contention-based MAC protocols as follows.

2.1.1 S-MAC

S-MAC [1] was proposed for energy efficiency based on IEEE 802.11 aiming at saving energy. It divides the time into frames whose length is determined by applications. There are work stage and sleep stage in a frame. S-MAC adopts an effective mechanism to solve the energy wasting problems, that is periodical listening and sleep. When one node is idle, it is more likely to be asleep instead of listening continuously to the channel to saving energy. The neighbours nodes reduce the idle listening by constructing a virtual cluster through consistency sleep schedule of negotiate mechanism. The advantage of S-MAC is that it reduces the transport delay by adopting traffic adaptive listening mechanism. Also, it uses beacons to reduce retransmission and avoid listening to unnecessary Data. Moreover, it reduces the control packet overheads and packet delay through message division and burst transmission. On the other side it has some drawbacks such as the period length is limited by delay and cache size, the active time depends on message transmission rate. Furthermore, the active time must adapt to highest traffic load to guarantee reliable and timely message transmission and the idle listening will relatively increase when traffic load is low.

2.1.2 T-MAC

The basic T-MAC protocol scheme, with adaptive active times, shows the basic scheme of the T-MAC protocol. Every node periodically wakes up to communicate with its neighbours, then goes to sleep again until the next frame. Meanwhile, new messages are queued. Nodes communicate with each other by using a request to send (RTS), clear to send (CTS), and data, acknowledgement (ACK) scheme, which provide both collision avoidance and reliable transmission. This scheme is well known and used, for example, in the IEEE 802.11 standard [2, 3]. A node will keep listening and potentially transmitting, as long as it is in an active period. It has some advantages such as T-MAC protocol is to reduce idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts. Also, it reduces the time in active state compared with S-MAC. The disadvantage of T-MAC has one major defect: the early sleeping problem. Sending request after time and full buffer first are proposed for solving the problem while the result is not satisfactory.

2.1.3 UMAC

UMAC presents a solution for improving performance on energy consumption for various wireless sensor network applications. It is based on the SMAC protocol and provides three main improvements on this protocol, e.g. various duty-cycles, utilization based tuning of duty-cycle, selective sleeping after transmission. The various duty cycle schemes are assigned for different nodes. Nodes have to exchange their schedules and synchronize clock with neighbours within a fixed period. However, they do not adopt the same schedules from their neighbours. In addition, time of the next sleep of a node is piggy-backed in ACK packets. It avoids unnecessary retries of RTS caused by missing update schedules from neighbours. Utilization based tuning of duty-cycle reflects to different traffic loads of every node in a network. Such variation corresponds to the diversity of performed tasks by a particular node and its location. Selective sleeping after transmission avoids unnecessary energy wastage. After a node finishes a transmission, it checks if there is its scheduled sleep time, and forces a sleep if it is. It does not introduce additional delays, since traffic is not expected to this node. In consequence, the proposed protocol improves energy efficiency as well as end-to-end latency.

In these contention-based MAC protocols, nodes are allowed for independent access to the medium and not required to form a cluster. Contention-based MAC protocols have good scalability and support node changes and new node inclusions well. And these protocols adopt different mechanisms to reduce energy waste on collision, idle listening, overhearing. The energy efficiency of contention based MAC-layer protocols, however, remains low due to collisions, idle listening, and excessive control overhead inevitable.

2.2 TDMA-based MAC

In contrast to contention-based MAC, scheduling based TDMA techniques offer an inherent collision free scheme by assigning unique time slots for every node to send or receive data. The first advantage of TDMA is that interference between adjacent wireless links is guaranteed to be avoided. Thus, the energy waste coming from packet collisions is diminished. Second, TDMA can solve the hidden terminal problem without extra message overhead because neighbouring nodes transmit at different time slots. Main TDMA-based MAC protocols are µ-MAC [2], DEE-MAC [3], SPARE MAC [4].

2.2.1 µ-MAC

The main idea of µ-MAC is to satisfy certain performance indicators of distribution rate, latency, etc, and then to the large extent, it will decrease the sending time of nodes to make the nodes enter into sleeping state. Nodes interactions include: sending, reporting, registering, and reservation. First, node requires the user to send request that includes data type, provided frequency of data, time session. In Fig.2, *S*3 sends a request, after which *S*2 registers and forwards. And then the source node *S*1 answers the request and sends the data report to the sensor.

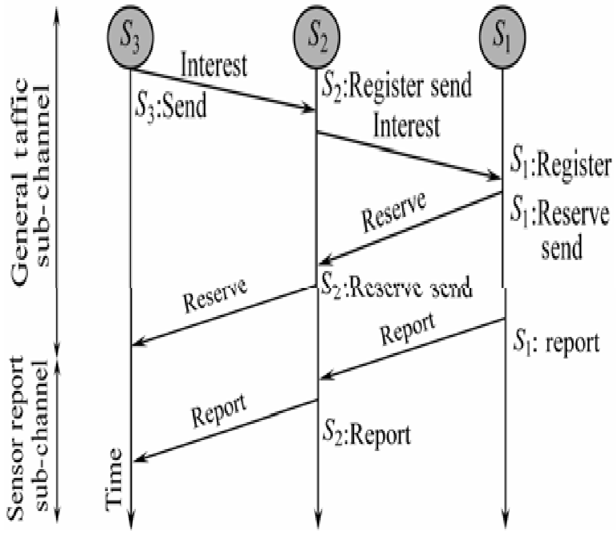

Fig.2 µ-MAC operation flow diagram

DEE-MAC [5] proposes an approach for energy consumption reduction by forcing the idle listening nodes to sleep using synchronization performed at the cluster head. Each cluster is dynamically formed based on the remaining power as all nodes contend to be the cluster head. Process of joining and leaving the cluster head is performed freely. DEE-MAC operations consist of rounds. Each of the rounds includes a cluster formation phase and a transmission phase. In the cluster formation phase, a node decides whether to become the cluster head based on its remaining power. The transmission phase comprises of a number of sessions and each session consists of a contention period and a data transmission period.

During the time of the contention period, each node keeps their radio on, and indicates interest to send a packet to the cluster head. After this period, the cluster head knows which node has data to transmit and it builds a TDMA schedule then broadcast it to all nodes. Each node is assigned with one data slot in each session. Based on the broadcasted schedule each of the nodes, having data to receive or send, is awakened. Clustering and TDMA based schemes present a rational solution to reduce the cost of idle listening in large-scale wireless sensor networks. However, the power of cluster head is easily depleted so the network partitions happen easily. SPARE MAC [6] is a TDMA based access control MAC protocol for data diffusion in WSN. The core idea of SPARE MAC is to save energy through limiting the impact of idle listening and traffic overhearing. To realize the goal, SPARE MAC adopts a distributed scheduling solution which assigns specific radio resources (i.e., time slots) to each sensor node for reception, summarized as Reception Schedules (RS), and spreads the information of the assigned RS to neighbouring nodes. A transmitting node can consequently become active in correspondence of the RS of its receiver only. The protocol dramatically decrease collisions and idle listening, however, the control packet overhead is very large, and the data delay is very large too. Although energy waste on collisions has been avoided, there are a number of drawbacks. Cluster, which is widely used in TDMA-based MAC, is difficult to dynamically change its frame length and time slot assignments, thus contributes to poor scalability. And the requirements on cluster head are higher than ordinary sensor nodes, especially power and computation capability. And TDMA-based protocols need strict time synchronization which results in high cost on hardware and high latency for data.

2.3 Hybrid contention-based and TDMA-based MAC

In recent years, there have been some hybrid proposals, which combine the advantages of contention-based MAC with that of TDMA-based MAC. All these protocols divide the access channel into two parts. Control packets are sent in the random access channel, and data packets are transmitted in the scheduled channel. The control channel schedules the data access. The hybrid protocols can gain high energy savings and offer better scalability and flexibility than any of contention-based MAC or TDMA-based MAC. Recently main hybrid protocols include Z-MAC [5], A-MAC [6] and IEEE 802.15.4 [7].

2.3.1 Z-MAC

Z-MAC [5] is a hybrid protocol, focuses on recapturing wasted slots by allowing nodes to compete for all slots with a bias towards the owner of the slot. This method allows nodes to recapture unused bandwidth without having to renegotiate the slot schedule. However, this removes the collision-free guarantee on message transmission and often cannot fully recover the bandwidth. It also does not solve the problem of requiring time synchronization amongst communicating nodes.

2.3.2 A-MAC

A-MAC [6] is a hybrid of CSMA and TDMA protocols, proposed recently for sensor network aiming at providing collision-free, non-overhearing and less idle-listening transmission services. And it is designed mainly for long-term surveillance and monitoring applications. In such applications, nodes are typically vigilant for a long time and inactive most of the time until something is detected. Some additional latency may be introduced at an acceptable level, while the life time of the WSN is dramatically prolonged. The main feature of A-MAC is that nodes are notified in advance when they will be the receivers of packets. A node is active only when it is the sender or the receiver, during other time it just goes to sleep. With this method, energy wastage is avoided on overhearing and idle listening. The core idea of A-MAC is TDMA as the baseline MAC scheme with CSMA to enhance the accessibility of the wireless channel. Basically, A-MAC allocates each node a certain number of unique time slots within its two-hop neighbours. Nodes then make use of these pre-assigned time slots to transmit the data packets without interference with others. A-MAC also has an advertisement scheme to allow the sender to notify its neighbours about its transmission schedule. With this scheme, only the receiver needs to be active during the transmission and other nodes can safely go to sleep.

2.3.3 IEEE 802.15.4

IEEE 802.15.4 is proposed for low-rate Wireless Personal Area Networks (WPAN). IEEE 802.15.4 is a hybrid protocol. It has a super-frame structure, in which a TDMA-based period is used for guaranteed access, and a contention-based period is used for non-guaranteed access. All nodes can turn off their radios and enter the sleep state in an inactive period. There is a coordinator that operating in the beaconed mode to maintain the synchronization of time-frames. However, IEEE 802.15.4 can also operate in ad-hoc based mode. In this case, there is only contention based period in the time-frame. In the contention based period, the traditional CSMA/CA is used for resolve the contention. There is no special design for energy conservation in IEEE 802.15.4 except a typical duty cycle controlling scheme. However, in these hybrid protocols control packet overhead is large and energy waste in transition between two operation modes is high. Moreover, in these protocols high latency is introduced due to transition between the two mechanisms.

2.4 Cross layer MAC focused on energy efficiency

Energy efficient MAC protocols presented above all focused on the design on the single MAC layer, without considering the correlation of layers in WSN, especially the useful information for MAC layer. Traditional network protocol stack is simple, however, it result in poor flexibility and low efficiency. Given the relation of each layer protocols, cross layer is a novel method to improve energy efficiency. In recent years cross layer MAC researches have been conducted for energy efficiency [10-11]. In [8] a cross layer design of the use of forward error correction (FEC) coding and the determination of the awake/sleep periods for narrowband wireless sensor networks is presented. This design takes into account, in a joint manner, the characteristics of the physical and the MAC layers. A new cross layer MAC protocol was presented in [9] called MAC-CROSS, which improved energy efficiency by making use of interaction between MAC layer and routing layer. In the MAC-CROSS algorithm, routing information at the network layer is utilized for the MAC layer so that it can maximize sleep duration of each node. In [10], direct interactions between the top Application layer and the bottom MAC/Physical layers were exploited. The traditional Network layer and Transport layer have been removed, thus simplifying the protocol stack. Some traditional function of the two layers is merged into the top and the bottom layers. In [11], a cross-layer mechanism called the CLMAC protocol was proposed. The protocol operates like the B-MAC protocol but it includes routing distance in the preamble field of the B-MAC. Without big routing table, it enables nodes to reduce control traffic routing overhead. In cross layer design, we should do optimization under energy and application requirements. And the useful information should be shared and transmitted among protocol layer to support the optimization mechanisms. MAC layer is influenced by other layer. Physical layer affects the MAC by changing its transmission power and modulation. Routing layer chooses proper wireless links to relay packets to the destination so the routing decision will change the contention level at the MAC layer. Congestion and rate control in the transport layer will change the traffic volume in each communication link while traffic types will have great effect on MAC layer. So cross layer method is a feasible way to improve the performances of MAC protocols and it need more research in depth.

3. CONCLUSIONS

In this paper, we have surveyed the existing energy saving MAC protocols. A MAC protocol needs to give optimum performance in the specific application area where it is used. Hence energy efficiency, though a primary requirement in a MAC protocol, depends on a particular network and application area. From the analysis on the energy efficient MAC protocols, we could find that: whatever contention-based MAC or TDMA-based MAC is still wasteful in energy and they could not adapt to the dynamic traffic well. Contention-based MAC protocols still waste energy by idle listening and large control packet overhead. The TDMA protocols need to keep strict clock synchronization among nodes; hence large latency and control packets are introduced. The hybrid MAC integrating the two kinds of mechanisms is better in energy efficiency than pure MAC using single mechanism. However hybrid MAC protocols are usually complex in transition mechanisms between contention-based and TDMA-based, in addition, these protocols are usually complex in implementation. Cross layer give us a novel method to make full use of information in protocol stack and could reduce energy consumption dramatically. However, cross layer method could significant increase the design complexity and diminish the advantages of layered method so it need extensive research. Nowadays with WSN applications and hardware evolving rapidly, how to achieve better energy efficiency in MAC for WSN is still a critical issue and need more studies.

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