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TDMA Protocols with Reduced Frame for Wireless Sensor Networks

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***Abstract* – TDMA-based MAC protocols, in its traditional form, suffer from low channel utilization and high message delay because of a long frame length needed to provide collision-free transmissions. In this paper, we introduce a class of TDMA-based protocols, called reduced-frame TDMA, which allow conflicting slot assignments, but provide every TDMA slot with a short time period dedicated for CSMA-based contention resolution mechanism. Simulation results indicate that the reduced-frame TDMA protocol significantly reduces the message delay and increases the maximum throughput without incurring significant penalty in energy efficiency compared to the traditional TDMA scheme.**

***Key words:* wireless sensor networks, medium access control, TDMA-based protocol, reduced frame TDMA**

I. INTRODUCTION

A wireless sensor network (WSN) is made of a number of autonomous and inexpensive sensor nodes each of which composed of sensors, a low-power radio transceiver, small amount of memory and processing capability as well as limited battery power supply. The common vision is to create a large WSN through *ad-hoc* deployment of hundreds or thousands of such tiny devices able to sense the environment, compute simple task and communicate with each other in order to achieve common objective [1]. Media access control (MAC) is a key component to ensure the successful operation of WSNs and it has obtained intensive research attention. A MAC protocol decides when competing nodes could access the shared medium to transmit their data and tries to ensure that no collisions occur. MAC protocol controls the activity of nodes' radio transceiver directly, and therefore makes a strong impact to the overall network performance and energy efficiency.

In the literature, time division multiple access (TDMA) and contention-based access are two major medium access approaches in WSNs. Contention-based MAC protocols achieve low power operation by introducing the duty cycling mechanism, in form of turning radio off part of the time. With S-MAC nodes synchronize their active/sleep periods: receiver only listens to brief contention period at the beginning of active phase, while senders contend using RTS/CTS control packets [2]. With low-power listening (LPL) a sender transmits a preamble prior to data transmission, and the receiver periodically wakes up for a short time to sample the medium [3]. With the SCP-MAC protocol senders use carrier sense multiple access (CSMA) to resolve contention before receivers poll the channel [4].

In order to avoid collisions, the TDMA-based MAC protocols establish a schedule where each node is assigned one or possibly multiple slots within a network-wide common frame. Full-frame TDMA protocols assign each node a fixed slot unique in its 2-hop neighborhood for transmission of one message in each frame [5]. This scheme is energy efficient and may provide higher throughput than contention-based protocols, under heavy traffic load. The downside is that 2-hop exclusive slot assignment usually requires a frame with a large number of slots, which increases the delay. Also, with TDMA overhearing is inevitable.

In order to cope with the drawbacks of both contention-based and TDMA-based MAC protocols, hybrid TDMA/CSMA solutions have been proposed. Z-MAC [6] is a hybrid TDMA/CSMA protocol where the contention resolution is performed at the beginning of the each slot, so that non-owners of a slot can contend for the slot if it is not being used by its owner. In that way, Z-MAC acts like a contention-based protocol under low traffic conditions and a TDMA-based protocol under high traffic conditions. The problems are the increased energy consumption due to constant carrier-sensing, and overhearing.

In this paper, we introduce a class of TDMA-based protocols, called reduced-frame TDMA, which allow conflicting slot assignments, buy providing every TDMA slot with a short time period dedicated for CSMA-based contention resolution mechanism. The advantage is clear: a smaller frame length will reduce message delay and improve throughput. On the other hand, a small number of available slots may increase the level of contention during individual slots. Thus, the main goal is adjusting the frame length to achieve the best performance with minimal price.

In Section II, we discuss the channel access mechanisms and full-frame TDMA protocols. Section III deals with the reduced-frame TDMA model and proposes heuristic slot assignment algorithm that minimizes inter-slot interference. In Section IV are shown the results of the simulations.

II. TDMA BASED MAC PROTOCOLS

In large multi-hop WSNs, slots within a TDMA frame need to be shared among several nodes. The spatial reuse of slots creates so called *slot assignment (SA) conflicts* between nodes. Presence of SA conflicts within a 2-hop neighborhood can causes the collisions if not properly handled. Taking into account the 2-hop SA constraint, we divide TDMA-based protocols into: *Full-Frame TDMA* protocols (FF-TDMA), with 2-hop conflict-free SA, and *Reduced-Frame TDMA* protocols (RF-TDMA) where 2-hop conflict-free SA is not guaranteed. FF-TDMA protocol corresponds to the traditional TDMA and provides interference-free transmissions. RF-TDMA is subjected to collisions due to the shortened length of frame and must be augmented with collision-avoidance mechanism, such as CSMA.

A. Channel Access Mechanism

FF-TDMA and RF-TDMA protocols require different mechanisms to access the channel in the reserved slots. With FF-TDMA the design of channel access mechanism is simple, since the nodes access the channel without contention for the medium or dealing with collisions. To deal with potential collisions, RF-TDMA needs a contention-resolution procedure at the beginning of each slot.

Channel access for FF-TDMA protocol. Fig. 1 illustrates the channel access activities for exchanging a data message in case of the FF-TDMA protocol. The receiving nodes briefly sample the channel at the beginning of slot, just long enough to detect a signal above the noise threshold. If there is no message to be sent, receivers will detect a clear channel and go to sleep immediately. Otherwise, receivers stay awake to receive the incoming data message. To avoid unnecessary overhearing of complete data messages, a receiver examines the destination address of a message immediately after receiving its header. If a data message is destined to another node, it immediately stops the reception and switches-off the radio. After successful reception of data message, the destination node may return an optional acknowledgment (ACK) message.

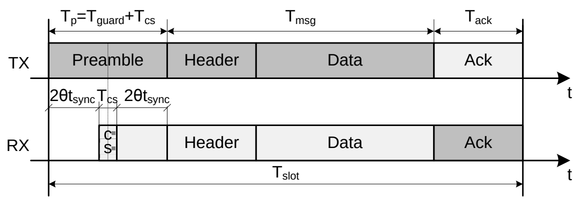

Fig. 1. Channel access scheme of FF-TDMA protocol.

Channel access for RF-TDMA protocols. With RF-TDMA protocol, a node may receive signals from two or more different senders at the same slot. This is called a collision and causes that no message is received correctly. In general, there are three types of collisions in a multi-hop wireless network (Fig. 2) [9]. Type_1 collision occurs when an intended receiver is also within the transmission range of another transmission intended for other nodes. Type_2 collision is due to multiple nodes attempting to send data messages simultaneously to a same node. Type_3 collision happens when an intended receiver simultaneously transmits to another node.

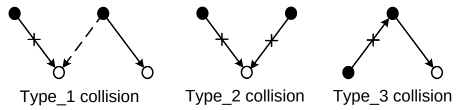

Fig. 2. Types of collisions in multi-hop wireless networks.

To deal with potential collision in RF-TDMA protocol, the transmitting nodes perform a simple CSMA-based contention-resolution procedure at the beginning of each slot. Every TDMA slot begins with a contention window (T_{CW}) which is divided into many short contention slots (Fig. 3). A node that wants to transmit in a particular TDMA slot randomly selects a contention slot and performs channel sampling. In case of idle channel the node proceeds, by sending the wakeup tone for the rest of contention window. In case of busy channel node gives up its attempt to transmit and switches to the receiving mode in order to avoid a potential Type_3 collision. Therefore, only the contention winner can transmit a message to its destination node. The node that is scheduled to receive in the slot, acts as in the pure TDMA approach. After the successful reception of a message, the receiver node immediately responds with an acknowledgement (ACK) packet within the same slot, which is sender's only indication of a lack of collision.

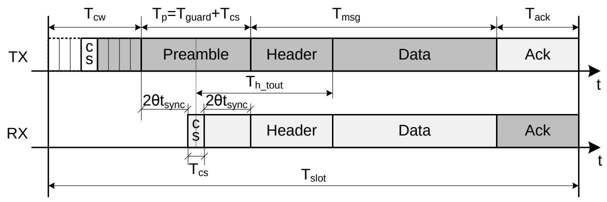

Fig. 3. Channel access scheme of RF-TDMA protocols.

The CSMA-based contention-resolution method suffers from the well-known problem of exposed and hidden terminals, which may lead to inefficient bandwidth utilization. The exposed-terminal problem occurs when a node that loses competition for the medium refrains from transmission even though it would not have interfered with the transmission of winning node. The hidden terminal problem occurs when sender nodes are outside radio range of each other. Due to a potential collision the sender has to buffer each sent data message until it receives an ACK for that message, so it could be retransmitted. To prevent repeated collisions of retransmitted data messages, the node waits a random number of frame periods (so called back-off delay) before the next attempting.

B. Full-frame TDMA

Most existing designs of TDMA-based MAC protocols are founded on 2-hop conflict-free SA. Consider a 2-hop conflict-free SA shown in Fig. 4(a). In this figure, the dark dots, *u* and *v*, represent nodes that share the same transmitting slot. Because these nodes do not have common neighbors, the collision in a case of their concurrent transmissions cannot occur. Such a scheme is thus able to reduce energy wasted by contention and collisions. Also, FF-TDMA provides guaranteed throughput for all nodes since each node can use its slot in every frame, no matter what are the actual traffic conditions, which makes it attractive for high data rate WSNs. However, each node must wake up in every slot owned by one of its neighbors, which increases energy wastage due to channel sampling and overhearing.

The FF-TDMA scheme also has a problem of choosing the optimal frame length. The short frame, although improving performance, can exclude some nodes from the network (due to the inability to assign every node with a 2-hop exclusive slot). The longer frame leads to a long channel access delay and a low throughput. To allow all nodes to participate in the network, the frame length has to be adapted to the densest area of network, which may lead to over-provisioning (wasted slots) in sparse areas. Full-frame TDMA protocols also suffer from utilization problems during periods of light traffic conditions.

III. REDUCED-FRAME TDMA

In RF-TDMA protocol, there is no constraint on minimum frame length, and nodes are allowed to choose their slots without strictly imposing the 2-hop exclusive slot ownership constraint. Two opposite tendencies affect the performance of RF-TDMA protocols. First, as the frame period is smaller, nodes will have a chance to use their slots more often, leading to a higher throughput and a smaller channel access delay. Second, as the frame length is smaller, slots will be reused within 2-hops more often, leading to a higher level of radio-interference during individual slots. This reduces the throughput and increases the channel access delay. The combined effect determines the overall efficiency of RF-TDMA protocols.

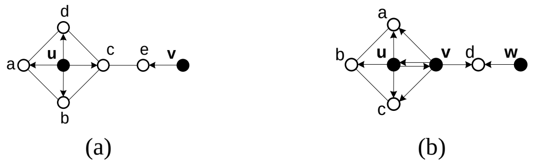

Fig. 4. Examples of TDMA slot assignment: (a) FF, (b) RF.

The manifestation of 1-hop and 2-hop SA conflicts will be explained on an example of SA in Fig. 4(b), where nodes *u*, *v* and *w* are assigned the same slot. There are one 1-hop SA conflict, between *u* and *v*, and one 2-hop SA conflict, between *v* and *w*. If at least one of nodes *u* and *v* intends to transmit to a node *a* or *b*, CSMA will prevent collision. However, if both nodes intend to transmit to their exclusive neighbors (e.g. *u* to *b*, and *v* to *d*), CSMA will cause exposed terminal effect. Therefore, the main negative effect of 1-hop SA conflicts in RF-TDMA is the reduction of node throughput. If a node shares the slot with *n* neighboring nodes, its effective bandwidth will not be 1 transmitted message per frame, as in FF-TDMA, but only $1/(1+n)$ transmitted messages per frame. On the other hand, 2-hop SA conflicts introduce hidden terminal effect between conflicting nodes. For example, concurrent transmissions from nodes *v* and *w* in Fig. 4(b) will cause collision at node *d* if at least one of these transmissions is intended for it. The fact that each node condenses all its transmissions within its own slot increases the chance for collisions caused by hidden terminals even under relatively light traffic load.

A. Slot Assignment Algorithm

Because in the RF-TDMA any SA is correct, there will never be a node in the network that is permanently hinder to use the medium. The simplest approach to SA problem in the RF-TDMA protocols is therefore to let each node randomly chooses its slot. However, this can create many SA conflicts which may lead to a significant performance loss. In this section, we present a simple heuristic approach for minimizing the number of 1- and 2-hop SA conflicts generated during slot assignment process.

At the beginning of our algorithm, the nodes are sorted in terms of their priorities (non-increasing order of their 2-hop neighborhood size). Node that has the largest priority among its two hops choose its slot first, others wait for slot decisions from other nodes within two hops that have larger priorities. The algorithm assigns slots to nodes in a way that minimizes the number of SA conflicts with already assigned nodes in 2-hop neighborhood. The primary criterion for selecting a slot for a given node is the minimization of additional 2-hop SA conflicts that will be created between the node and already assigned nodes. The secondary criterion is the reduction of additional 1-hop SA conflicts.

IV. SIMULATION RESULTS

We implement our TDMA protocols in a custom WSN simulator build in C++. All our simulations are based on the simulation of the same WSN composed of 200 nodes randomly placed within a circular area of radius 100 m. The node density is set to 6 (FF-TDMA schemes require at least 16 slots per frame). All nodes are equipped with single half-duplex transceivers. The energy consumption of a single channel sampling operation is 17.3 μJ, for a low-power listening approach. Transfer rate of 19.2 Kbps is assumed. Packet length is fixed to the 64 bytes.

Performance is evaluated for two scenarios: the maximum traffic load and the variable traffic load. The metrics are: the normalized throughput (NT), the average message delay (AMD), and the energy overhead ratio (EOR). The throughput is defined as the ratio of the average number of packets that are successfully received at each node to the total simulation time under certain traffic load. The average message delay is average time for a data message to be received by the destination node after it was queued in a source node's buffer.

As it can be seen in Fig. 6, at maximum traffic load, the available bandwidth of one transferred message per node per frame can be fully utilized only with the FF-TDMA protocol. Reducing the number of slots per frame leads to

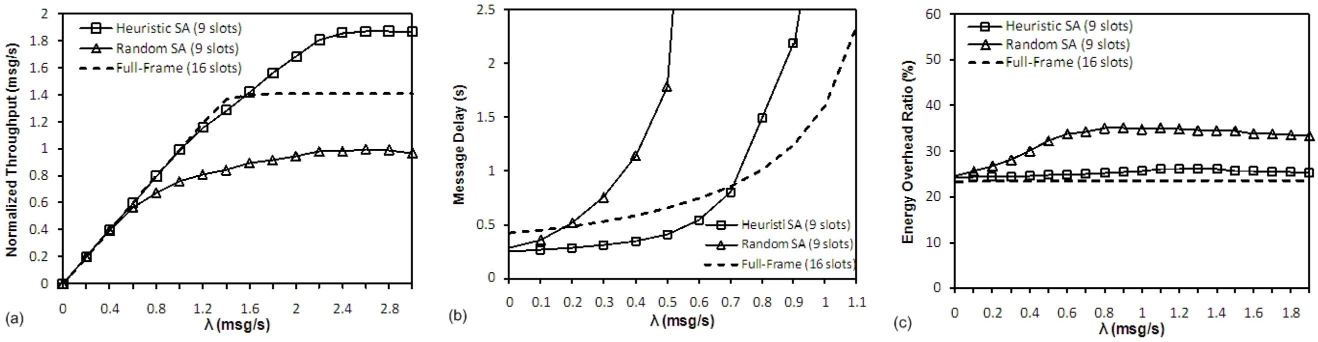

Fig. 5 Performance under varying traffic load: (a) normalized throughput, (b) message delay, (c) energy overhead ratio.

increase of the bandwidth available to nodes. At the same time, the occurrence of SA conflicts generates more collisions, which reduces *maximum NT* (MNT) and increases the EOR. As it can be seen on the Fig. 6(a), the highest MNT achieves our RF-TDMA protocol with heuristic SA, for the frame length 9,which is 33.2% improvement over FF-TDMA, and with increase of energy of only 2% (see Fig. 6(b)). At the same time, random SA achieves much lower results compared to both other schemes.

(a)

(b)

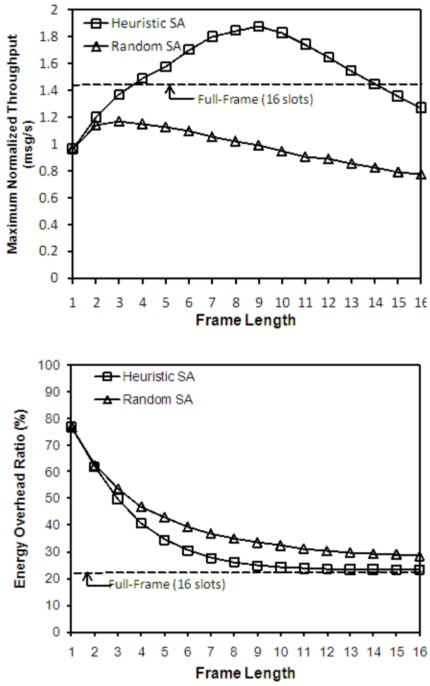

Fig. 6 Performance under maximum traffic load: (a) maximum normalized throughput, (b) energy overhead ratio.

In the next set of simulations we assume that the RF-TDMA protocols are configured with the frame length that maximizes their MNT. When the traffic load increases, the normalized throughput increases linearly and finally saturates at the level of MNT (Fig. 5(a)). As it can be seen in Fig. 5(b), under very low traffic load RF-TDMA protocols provides smaller AMD than FF-TDMA. With increasing traffic load, the AMD goes up, but faster for the RF-TDMA, due to CSMA contention, and retransmissions after collision. At very low traffic load, all protocols have about the same EOR, mostly due to overhearing (Fig. 5(c)). The EOR of FF-TDMA does not change with traffic load. In RF-TDMA, beside the message overhearing, there is an additional amount of energy wasted due to collisions, message retransmissions and CSMA contention. Since this is less evident with heuristic scheme, it has significantly smaller increase compared with random scheme.

V. CONCLUSION

In this paper we have studied the reduced-frame TDMA protocols: a hybrid TDMA/CSMA protocols with a CSMA-based contention resolution mechanism at the beginning of the each slot. We proposed heuristic SA scheme that minimizes SA conflicts. Simulation result shows that our proposed heuristic SA algorithm improves performances with minimal increase in energy consumption. It also shows that the effective slot-assignment scheme is crucial to take benefit from the reduced-frame TDMA approach.

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