Smart Hybrid Frame Scheduling to Improve Energy Efficiency in Wireless Sensor Network

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ABSTRACT

Energy constrained hybrid CSMA/TDMA based Medium Access Control (MAC) scheduling has largely been ignored in litureture regarding Wireless Sensor Networks (WSN). In this paper, we propose a new smart framing scheduling scheme to improve energy efficiency for CSMA/TDMA hybrid MAC designs in WSN. The proposed hybrid scheme combines CSMA and TDMA functionalities together, while obviates their shortcomings. By introducing an extra frame scheduling slot, senders can broadcast their transmission schedule to notify neighbor nodes. Thus, all neighboring nodes will know neighbors' behavior in the upcoming slots. By means of the proposed scheduling, each single node is aware of the exactly schedule of its neighbor nodes, and it can go to sleep mode smartly if it has received all the data and has no further tasks in the current round. The simulation results show that such scheme of smart frame scheduling has achieved significant total sleep time and energy efficiency improvement.

Keywords: Energy Constrained Frame Scheduling, TDMA-CSMA MAC, Wireless Sensor Networks.

1 INTRODUCTION

Real-time surveillance and environment monitoring applications in Wireless Sensor Networks (WSN) usually require sensor nodes to be operated in low power and sleep mode to extend the network life time [1]. These inborn natures of WSN make energy efficiency as the first priority, and the throughput, latency and fairness are all with low priorities [2]. The smooth operation of energy oriented sleep and duty cycle management any WSN depends to a large extent, on the effectiveness of the scheduling algorithms in Medium Access Control (MAC) layer and Physical layer.

Traditionally, state-of-the-art wireless channel access schemes are classified into two broad categories: contention based medium access and reservation based medium access [3]. A common and popular MAC paradigm in wireless networks is CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance), which is a contention-based medium access scheme. The superb advantages of CSMA/CA based channel access schemes are simplicity and robustness, because CSMA/CA based channel access schemes do not require Access Point (AP) based infrastructure support [4]. Ad hoc based network can be randomly deployed without any time synchronization among the sensor node, thus the network planning cost is significantly reduced. Unfortunately, collisions may happen in any two hop neighbors because of the contention. Although RTS/CTS based schemes can alleviate the hidden terminal problem and reduce contention significantly, they incur high communication overhead and do not perform well with respect to intensive-contention high-volume traffic according to [5] and [6]. Furthermore, the communication overhead brought by RTS/CTS packet exchange leads to extra energy consumption in WSN, which is unfavorable for extending WSN network life-time.

On the other hand, reservation based medium access paradigm TDMA (Time Division Multiple Access), can solve the hidden terminal problem and contentions without extra message overhead, because it schedules transmission slots of neighboring nodes to occur at different times. Unfortunately, TDMA based schemes also have a lot of problems such as requiring near perfect time synchronization, and they are hard to be used directly in a scalable network due to the high network planning overhead. Recent research in [4] proposes a hybrid CSMA/TDMA scheme called Z-MAC, a novel way to combine CSMA and TDMA together. It can smartly adapt to the level of contention in the network. When the traffic and contentions are low, Z-MAC behaves in CSMA mode; when the traffic and contentions are high, it uses a TDMA based hint scheme to improve contention resolution. However, in Z-MAC all the nodes have to constantly perform Low Power Listening (LPL) in all time slots, in order to check the incoming data. Because of the features of mixing contention-based scheme and timing slotted schedule, this constant LPL listening issue is a challenging problem in nature for all hybrid CSMA/TDMA scheduling schemes.

To further improve the energy efficiency in hybrid MAC scheduling, in this paper we introduce a new frame scheduling functionality into hybrid CSMA/TDMA MAC's such as Z-MAC, to eliminate unnecessary low power listening efficiently. In the proposed scheme, because each node could know its schedule and its neighbors' schedule exactly, it can smartly go to sleep mode to achieve more energy saving.

Studying the hybrid CSMA/TDMA scheduling schemes in WSN MAC has largely been ignored in literature. Most of the MAC protocols for WSN have been proposed based on conventional CSMA/CA wireless protocols, because of their effectiveness in collision avoidance. Specifically, most of these works for conventional wireless protocols are shown in the evolution of IEEE 802.11 protocol family such as [7] - [8], [12]-[15]. However, these researches are mainly focusing on the throughput optimization and delay minimization, which are unsuitable for energy-constrained WSN designs because of the high priority of energy efficiency.

On the other hand, MAC designs in WSN are seldom hybrid CSMA/TDMA based due to high design complexity.

For example, one of the most popular WSN MAC protocol S-MAC [9] is mainly a low power CSMA contention based protocol with very preliminary TDMA based scheduling. The basic idea in S-MAC is that time is roughly divided into active period and sleep period. In the beginning of each active period, the nodes exchange synchronization information. After the synchronization, data may be transferred in the remaining active period using RTS-CTS-DATA-ACK handshakes. The authors of S-MAC also extended the adaptive listening functionality, effectively trading off energy to latency.

T-MAC is proposed in [10] to improve S-MAC's energy efficiency, by introducing adaptive duty cycle instead of fixed duty cycle. After synchronization period and the data transferring in the active period, a timeout window (TA) is applied to determine the node's further activities. If no data reception occur during the TA period, the node then goes back to sleep mode. Such kind of adaptive duty cycle management functionalities in T-MAC performs better energy saving than S-MAC, especially in variable workloads.

B-MAC is proposed in [6], which is also a CSMA based MAC protocol in WSN, has a simple MAC core and allows application to implement its own MAC through a well defined interface. It also applies LPL (Low Power Listening) and CCA (Clear Channel Assessment) to achieve adaptive throughput and higher energy efficiency. According to the evaluation in [6], B-MAC is shown to have higher throughput and energy efficiency than S-MAC and T-MAC. However, the hybrid CSMA/TDMA scheduling problem is not addressed in B-MAC.

Z-MAC is recently proposed in [4], which is based on B-MAC, uses CSMA as the baseline MAC scheme, but uses a TDMA scheduling as a hint to enhance contention resolution. In Z-MAC protocol, time slot assignment is performed during the time of deployment. Thus, higher overhead is incurred at the beginning. Its design philosophy is that the high initial overhead is amortized over a long period of network operation, and the initialization overhead is eventually compensated by the improved throughput and enhanced nergy efficiency. The significant difference between Z-MAC and TDMA is that, a node may transmit during any time slot in Z-MAC.

Z-MAC is an excellent MAC protocol in terms of its adaptive feature compared with most existing MAC protocols in WSN research community,. However, Z-MAC requires all the receivers constantly performing LPL to check incoming data, because of the poor coordination between senders and receivers. The frame scheduling functionality proposed in this paper will give extra coordination chances to senders and receivers. Thus the proposed scheduling scheme further increases the sleep time and energy efficiency as described in later sections.

2 PROBLEM FORMULATION

The Z-MAC protocol is designed based on B-MAC due to its high versatility and energy efficiency. Additionally, Z-MAC combines the advantages of CSMA and TDMA together, while offsetting their shortcomings. Under low contention levels, CSMA can achieve high channel utilizations; under high contention levels, TDMA can perform better channel utilization. Before a node transmits during a slot, it always performs carrier-sensing and attempts to transmit a packet when the channel is clear. However, the owner of that slot always has higher priority than other non-owners in accessing the channel. The priority is implemented by adjusting the initial contention window size in such a way that the owner is always given earlier chances to transmit than non-owners. By mixing the ideas of CSMA and TDMA, Z-MAC becomes more robust to timing failures, time-varying channel conditions, slot assignment failures and topology changes than a stand alone TDMA; in the worst case, it always falls back to CSMA.

Z-MAC includes four major parts of functionalities: neighbor discovery, slot assignment, local frame exchange and global time synchronization [4]. The neighbor discovery and slot assignment as well as the global time synchronization parts are unchanged in our approach, so the reader can directly get reference in [4]. We further propose the scheduling frame exchange part, introducing a frame scheduling time slot, to let senders advertise the buffered data and intended destinations. This scheme can reduce receivers' LPL, because the receivers know when it should go to sleep mode after fully data reception.

The slot allocation approach of Z-MAC is illustrated in Figure 1. After neighbor discovery using DRAND as discussed in details in [4] and [11], each node constructs a neighbor list in two hops. Figure 2 shows an abstract example of this two hop neighbor topology. Based on the topology information, the DRAND [11] constructs the time slot allocation. Each node is assigned at least one slot for transmission and receiving, and each node can contend other transmission slots if the owners of those slots have no data to transmit. For the nodes in receiving mode, LPL is used.

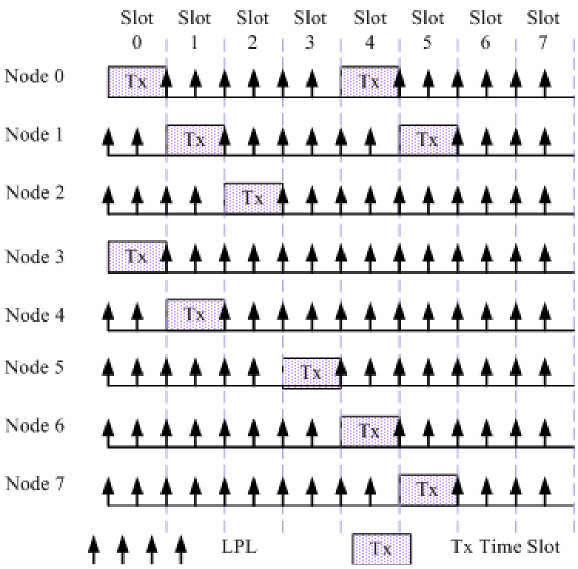

Figure 1: Hybrid CSMA/TDMA Slot Allocation

All the nodes in Z-MAC must be constantly performing LPL because none of them know which nodes will send data and when the data comes. Thus all the nodes spend extra and unnecessary time to check if there is data transmitting to them. If a node is aware in this round which nodes will send data to it, and how many bytes data will be sent, then it can smartly executes LPL. If it has already collected all the data it needs in this round, and checked the correctness of the data (usually by evaluating the CRC checksum), it can turn off the radio module and go to sleep mode to further energy saving.

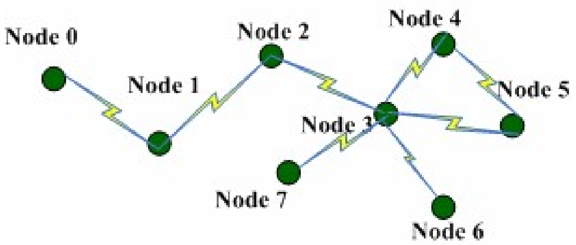

Figure 2: An Abstract Example of Two Hop Neighbor Topology

3 PROPOSED SMART FRAME SCHEDULING APPROACH

The proposed frame scheduling scheme is designed to solve this problem in this paper. The synchronization mechanism is designed the same as Z-MAC. Thus the proposed frame scheduling scheme does not introduce any further synchronization overhead compared with original Z-MAC. We select slot 0 in every scheduling round as the scheduling slot where each node is on for receiving advertisement. The transmission node will contend for the medium and channel in this scheduling slot. Once getting the access, it broadcasts a short packet named scheduling frame containing the source and destination addresses, as well as the length of data which will be transmitted to the corresponding destination address.

The structure of the proposed scheduling frame is shown in Figure 3, where every node has a receiving scheduling table described in Figure 4. When a node receives a scheduling frame from its neighbor, it checks the destination address list in the received scheduling frame (Fig 3). If its address is in the destination address list, it adds an entry in its receiving scheduling table (Fig 4). The duty cycles in the scheduling slot finish when all the nodes' advertising transmissions are done. After that all the nodes go to sleep mode for the remaining part of the scheduling slot.

DstAddr0 (2bytes) : Length0(2bytes)	… …	… …	DstAddrN-1 (2bytes) : LengthN-1(2bytes)	SrcAddr (2bytes)

Figure 3. The Proposed Scheduling Frame Structure

The CSMA/TDMA slot starts at slot 1, other than slot 0. This is the significant difference between original Z-MAC and the proposed scheme. Figure 5 shows the illustration of applying the proposed adaptive frame scheduling scheme onto the exemplar abstract WSN in Figure 1. In the following part of this section, we give a detailed description on how the proposed scheme works. Note that we do not loose the generality of our proposed approach because the example in Figure 1 is general and typical without any specific restriction on the network topology and traffic. Assume Node 0 has data to for node 1, and node 4 has data for node 5.

All other nodes have no data to be transmitted in this round. At the beginning of the scheduling slot, both node 0 and node 4 perform CCA and channel contention. Because they are not one hop or two hop neighbors, they both acquire the channel and broadcast their scheduling frame.

SrcAddr0	Length0
SrcAddr1	Length1
……	……
SrcAddrN-1	LengthN-1

Figure 4. The Proposed Receiving Scheduling Table

Then node 1 receives the scheduling frame from node 0 successfully; and both node 3 and node 5 receive the scheduling frame from node 4 successfully. Node 3 is not in the destination address list, so it simply discards the frame. Node 1 adds node 0 to its receiving scheduling table and node 5 adds node 4 in the same way. In the proposed approach, node 0 and node 4 re-run a random back-off to re-broadcast the schedule to reduce the possibility of broadcasted frame collision due to hidden terminal problem.

In a way similar to T-MAC, a time out value TA is introduced in the proposed approach. In a TA time slice, if a node does not percept any neighbors' communication, it goes back to sleep mode for the remaining time of the scheduling slot. In slot 1 the data transmission between node 0 and node 1 is performed. Because node 0 is the temporary owner of slot 1, it takes slot 1 as the transmission slot.

Because node 1 already added node 0 to its receiving scheduling table as shown in Figure 4, and it knows that slot 1 is already assigned to node 0, it turns radio to Rx mode. Once node 1's receives the data correctly and meets the requirement in the scheduling table, its duty cycle in this round is finished, and it goes back to sleep. On the other hand, if node 0 can not finish transmission in slot 1, it will contend channel in other slots. Then node 1 goes to LPL mode to receive the remaining data. After fully receiving data, node 0 and node 1 both go to sleep mode until the beginning of the next transmission round.

Then we observe the data transmission between node 4 and node 5. It is assumed that node 3 will transmit data because it is the owner of slot 1. But node 3 has no data to transmit while node 4 has data to transmit. Thus node 4 contends the channel from node 3. Then it transmits long preamble followed by data in slot 1. On the other hand, node 5 runs LPL at slot 1, since it does not know which transmitting slot is to be taken by node 4.

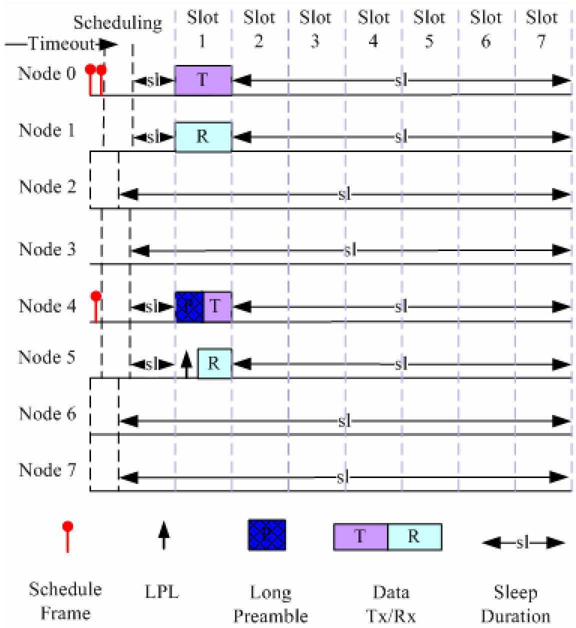

Figure 5. Slot Allocation with Proposed Smart Frame Scheduling

After node 5 successfully checked the long preamble from node 4, it turns to Rx mode. This adaptive LPL approach significantly reduced the switching radio on and off event, and thus saves considerable extra energy.

4 SIMULATION

In this section we compare the proposed frame scheduling scheme with the original Z-MAC scheme in terms of sleep time and energy consumption. The experimental parameters are listed in Table 1 according to Z-MAC and B-MAC [4] [6]. Traffic data used in simulation are from a single TinyOS packet with payload 36 bytes to 3600 bytes.

In Figure 6 we show the comparison of total sleep time (of all the nodes other than a single node). it is clear that with the proposed frame scheduling, the total sleep time increases considerably. With the increasing of application layer traffic load, it is reasonable observed that the total sleep time decreases. This is because in high traffic scenarios, the original Z-MAC wastes less percentage of LPL time. This figure shows the improved sleep time performance of our frame scheduling scheme compared to the original Z-MAC, particularly for the relatively lower traffic situation.

Table 1: Parameters used in simulation.

Symbol	Parameter explanation	Value
tPreamble	Preamble Length (bytes)	271
tPacket	Packet Length (bytes)	462
tDataRate	Link Level Data Rate (kbps)	19.2
cSleep	Sleep Current (mA)	0.03

cInitRadio	Initialize Radio Current (mA)	6
cRx	Receiving Current (mA)	15
cTx	Transmission Current (mA)	20
tVol	Voltage supply (V)	3
tInitRadio	Radio Initialization Time (ms)	0.5
tCrystal	Crystal Startup Time (ms)	1.5
tLPL	LPL Sample Duration (ms)	0.5
tSlotSize	TDMA Frame Size (ms)	50
tLPLIntv	LPL Check Interval (ms)	10

In Figure 7 we show the total energy consumption comparison. The total energy consumption with frame scheduling is lower than that of original Z-MAC without such scheduling. The reason is that in Z-MAC, each node does not know its neighbors' schedules. Thus all the nodes have to perform extra unnecessary LPL to check if there are data available or not. Further more, frequent switching radios on and off consumes a lot more energy than totally going to sleep mode. Although the total sleep time increases a lot with the proposed frame scheduling scheme as illustrated in Figure 6, the total energy efficiency improvement is not that much as the total sleep time increases. This can be attributed to the superb performance of LPL [6]. The overhead of the smart hybrid frame scheduling scheme is the consumed initial slot for exchanging control information, which introduces extra latency for data delivery. However, considering the high priority of saving energy in battery-operated WSN and low priority of end to end delay, this smart frame scheduling scheme is worthwhile due to the considerable gain in sleep time improvement and the enhanced energy efficiency. Similar to Figure 6, at relatively low traffic level, the performance of the proposed smart frame scheduling achieves more energy saving. At high traffic level, the energy consumption with smart frame scheduling is still consistently lower than Z-MAC. Again, the reason is that in high traffic scenarios, the original Z-MAC wastes less percentage of LPL time.

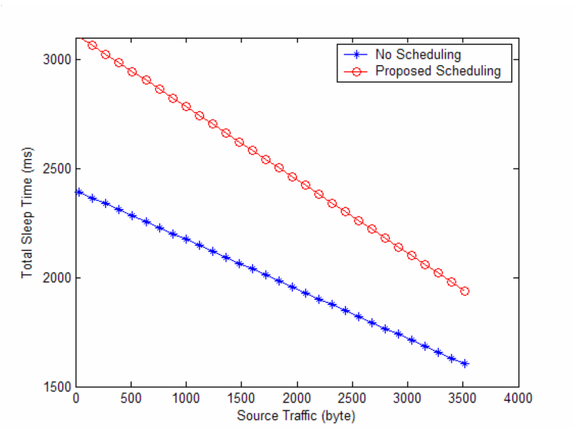

Figure 6. Total Sleep Time Comparison: without the proposed frame scheduling and with the proposed frame scheduling

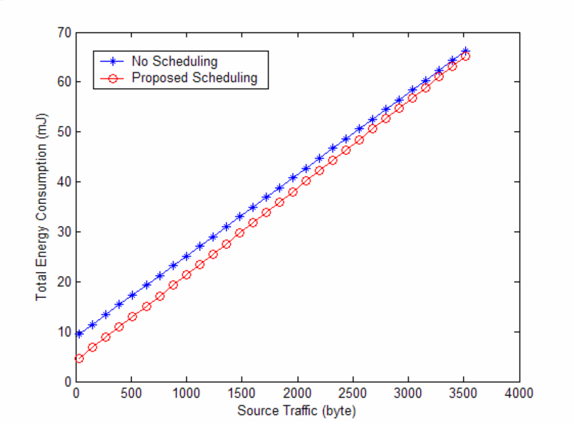

Figure 7. Total Energy Consumption: without the proposed frame scheduling and with the proposed frame scheduling

5 CONCLUSION

In this paper, we have proposed a new smart hybrid frame scheduling scheme to increase sleep time and to reduce energy consumption in CSMA/TDMA based WSN MAC designs. Although LPL achieves considerable energy saving by significant reducing idle listening, the proposed scheme is more effective to smartly turn the radio off when necessary. With this proposed scheduling, each node knows exactly the schedule of its neighbor nodes, so it can cleverly stop unnecessary LPL once it successfully receives all data. Sleep time and energy efficiency performances of the proposed scheme are compared with Z-MAC. Simulation results show the proposed smart frame scheduling scheme can further enhance Z-MAC's total sleep time and energy efficiency especially with low application traffic.

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