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Performance Analysis of CSMA/TDMA Hybrid-MAC for Wireless Sensor Networks

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Abstract

A new approach for energy efficient sensor networks that maximizes the life of the sensor networks which maintaining desired quality of service attributes related to sensed data delivery is presented. The IEEE802.15.4 as a standard for low rate wireless personal area network (LR-WPAN) is an applicative choice for wireless sensor networks. Due to the advantages of this standard and its capabilities for more specification to wireless sensor networks, we were persuaded to resolve some of its proven weaknesses in such environments. The slotted CSMA/CA method utilized in beacons-enabled mode of 802.15.4 causes an unacceptable level of energy consumption in conditions like high loads. To overcome these issues, we adopted method the capability and flexibility provided by CSMA/CA makes it work at low contention and TDMA makes it work at high loads by taking advantage of a greedy algorithm for TDMA slot allocation. Using these techniques we obtained improved results such as reduced energy consumption, improved throughput and decreased end to end delay. The new ATDMA and routing algorithm's scale well and converge fast for large scale dynamic sensors as shown by our extensive results using the Network Simulator (NS2).

Keywords: *CSMA/CA,IEEE802.15.4,Energy,LR-WPAN, TDMA,Wireless sensor Networks,*

1. Introduction

Improvement of electronic devices and micro-electronic chips has suggested wireless sensor networks as a solution for networks applications like video surveillance, traffic monitoring, object detection and tracking systems, etc[1]. Each node has one sensor, embedded processors and low-power radio and is normally battery operated. Therefore, energy for sensor networks should be managed carefully to extend the lifetime of sensors.

Since the utilized medium access control (MAC) protocol takes control of a node's radio- as the most energy consuming part of a sensor node-MAC protocol has a very important role in wireless sensor network design. Having a revision on suggested methods of wireless sensor data communication, MAC protocols can be divided into two main categories: contention based and TDMA-based protocols.

These protocols provide mechanisms for avoiding and resolving collisions [3]. TDMA-based protocols like TRMA and μ-MAC are collision free because each node has a designated time slot in which only that particular node transmits. There are also hybrid CSMA/TDMA [16] methods proposed. Z-MAC[9] is an example of such hybrid protocols which works adaptively, and goes toward a fully TDMA environment as the traffic increases. In spite of the number of methods designed for wireless data communication, there is still no standard specified for wireless sensor networks. Features like low duty cycle and self-organization of 802.15.4 standard-which are specific characteristics of wireless sensor networks-make this protocol a more attractive choice. According to the collision avoidance mechanism is not efficient in case of a large-scale WSN.

Also with high offered loads, the slotted CSMA/CA utilized in 802.15.4 [16,12] causes lower network throughputs due to collisions resulting from of multiple simultaneous transmissions, at the beginning slotted of a new super frame. The weaknesses caused by the slotted CSMA/CA were our motivation for designing a new hybrid MAC [9]for WSN environments. Organization of this paper shows that chapter 1 introduction about sensor networks,Chapter2 overview of 802.14.5standard. Chapter 3 Related work , Chapter4 ApplyingTDMAin IEEE802.15.4 contribution,Chapter5 Simulation results using NS-2.

2. Overview of 802.15.4 Standard

This 802.15.4[13] supports both peer-to-peer and star topologies. In star topology the communications are established only between network devices and a coordinator which is a full-function device (FFD) capable of relaying messages. In peer-to-peer topology a connection can be made between any two devices. Two operational modes are defined in this standard beacon-enabled and non-beacon mode. In non-beacon mode, like 802.11, channel access is only based on CSMA/CA[11].But in beacon-enabled mode the coordinator transmits a special-formatted frame named “beacon frame” in specified time intervals by which the devices synchronize themselves for accessing the channel[12]. The time intervals between two beacon frames are called the beacon interval, and get divided to an active and an optional inactive period. Devices are in sleep mode during the inactive period for energy saving purposes. The length of the active period is named as “super frame duration” and contains 16 equal time slots. The active period also consists of a contention access period (CAP) and a contention free period (CFP). The border between the CAP and CFP is specified by the variable final CAP slot in the beacon frame. The CFP-which is managed by the coordinator, is used for applications demanding higher quality of service. Time slots in the CFP could be assigned to nodes only after they send a request to the coordinator. During the CAP, devices access the channel with a slotted CSMA/CA method. For specifying the beacon interval (BI) and the super frame duration (SD), coordinator sets two beacon orders (BO) and super frame order (SO) values in the beacon frame. These two parameters follow the O≤SO≤BO≤15 constraint .

3. Related Work

Most protocols suggested for MAC layer of wireless sensor networks take advantage of either TDMA or CSMA/CA. Contention protocols provide advantages such as scalability, flexibility and self-organization. Besides, they have disadvantages such as idle listening and the overhead of using control packets like RTC/CTS for synchronization. TDMA –based protocols avoid collisions [3] and idle listening by assigning pre specified time slots to the network nodes. Though, these methods have difficulties in dynamically changing networks in which nodes enter and quit frequently. Partitioning the space among network nodes and efficient management of time slots are important challenges in TDMA-based protocols. Other protocols like Z-MAC use hybrid models. Z-MAC[9] utilizes an adaptive method of channel access which makes it work like CSMA in low contention and similar to TDMA model in order to reduce energy consumption caused by unnecessary listening. In this model each node intelligently goes to sleep and reduces energy consumption.

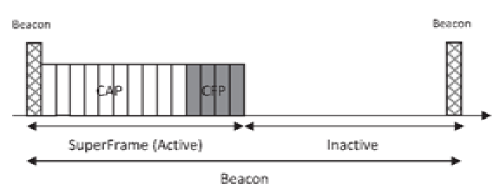

Fig. 1 Super frame structure in Beacon-enabled mode

4. Applying TDMA in IEEE 802.15.4

The main idea is to add a dynamic TDMA period into CAP of 802.15.4 standard. Based on characteristics provided by TDMA[16] energy consumption throughputs are improved and end to end delay is decreased in some conditions. In this model, the coordinator takes the role of assigning TDMA slots to network nodes. As a result, the main issues of TDMA- based protocols are resolved: first is the coordination of nodes, which is mostly overcome by the role of coordinator and the beacon frame it transmits in predefined time intervals (BI); and second is the under-utilization problem in TDMA networks which is also handled in high load by taking advantage of a greedy algorithm for TDMA slot allocation. When using TDMA, some active period slots will still belong to the CSMA method. Therefore the MinCAP Length constraint of standard is satisfied and also the scalability and flexibility provided by CSMA/CA are preserved. For example unlike pure TDMA networks, entrance of new nodes will not be a challenging problem. In the rest of this section we changes which have been applied to the standard protocol in order to make a hybrid CSMA/TDMA[11] environment.

4.1 Beacon frame modification:

The same as802.15.4 [12] the beacon frame has to specify how the CAP and the TDMA slots are divided between network nodes. Accordingly, the GTS descriptor in GTS list field and the GTS[2] specification field in 802.15.4 standard are used after some partial modifications. As displayed in figure-2, in GTS descriptor of GTS field each field has three parameters: node address (n bits), start slot of the node's GTS, and the number of slots assigned to that node. We provide enough space for adding TDMA by little modifications in this structure and the four reserved bits in GTS specified field.

Bits: 0-15	16-19	20-23
Device Start Address	GTS starting slot	GTS Length

Fig.2 Format of GTS Descriptor

As mentioned earlier, the four reserved bits represent the number of slots belonging to the TDMA period. In this way up to 16 slots could be used for TDMA period. In addition a number of bits are required to specify where in the active period these TDMA slots reside and which nodes they belong to. We gain these bits by modifying the GTS list. The goal is to occupy a number of bits in beacon frame for specification of TDMA slots without changing the beacon frame length or making any major changes in the frame structure. Thus, semantics of the GT declaration bits have a minor change. Remind that the border between the CAP and the CFP is specified by the variable final CAP slot in the super frame specification field. We specify the border between GTS and TDMA in GTS[2] specification field by two new variables "GTS descriptor count" and "TDMA descriptor count" which are represented by the reserved bits.

The new idea is that the GTS descriptors are sorted by the ascending order of their start time. In this way there will be no need to the four bits indicating the GTS start time, since every node can easily calculate its access start time by adding up the GTS lengths of its predecessor nodes. This simple calculation will not add considerable processing overhead or additional energy consumption in comparison with 802.15.4. We also set that no more than one TDMA slot is given to a node in each TDMA assignment. With these two assumptions only 16 bits are needed to indicate the short address, and the other 4 bits show the number of slots GTS allocation is only specified with 16 bits exactly the same as one TDMA slot allocation. To show the details of TDMA and GTS slot allocations, two sample scenarios are discussed below:

Scenario1: Assume a case in which none of the nodes has requested GTS[2]. Here we can use the whole GTS list space for giving TDMA slots to the nodes. Length of the GTS list space is equal to the maximum number of GTS descriptors (seven descriptors) multiplied by length of each GTS descriptor (24 bits), which will give us 168 bits for putting 16 bit device short addresses. Therefore 10 node addresses can be placed in this space. In other words, up to the 10 last slots of super frame duration can be assigned to nodes by TDMA method.

Bits: 0-2	3-6	7
GTS Descriptor count	Reserved	GTS Permit

Fig. 3 Format of the GTS specification field

Scenario2**:** In this case there are two GTS requesting nodes. One of them asks for one, and the other asks for GTS slots. As mentioned earlier, the single slot GTS request is seen as a TDMA slot. Suppose the network condition is so that the proposed algorithm assigns most possible space to the TDMA protocol. Therefore 20 out of 168 GTS list bits belong to declaration of the 3 slot GTS and the rest of this space is used for TDMA slot allocations. Note that one TDMA slot is preserved for one slot GTS[6] requesting node. Therefore the coordinator can leave up to 8 slots {(168-20)/16-1} to TDMA. This is done only if it is not in contrast with the aMinCAPLength constraint. Figure-4a and 4b display the GTS list and GTS specification field in such condition, when TDMA denotes the Devices Short Address of the node to which i^{th} TDMA slot is assigned.

4.2 Proposed hybrid CSMA/TDMA coordination algorithm:

The coordinator needs an algorithm[4] to determine the border between TDMA and CSMA in Contention Access Period. Here we discuss how coordinator gains the information needed by this algorithm. Then we explain how the algorithm decides about the length of the TDMA period and how TDMA slots are assigned to nodes without under-utilization occurrence. As it will be seen later, channel utilization is evaluated as a simple function of number of slots used, number of un-used slots and number of slots having collision. Two parameters are considered for determining the border between CSMA and TDMA: channel utilization level in CAP; and the amount of pending data in node's queues. For maintaining the queue state of network nodes, the coordinator keeps an array containing the queue states of all nodes. Each array cell belongs to one network node and has the initial value of 0. To have an estimation of the queue states coordinator calculates the level of network node by monitoring the frequency of packet reception and network traffic,

Bits:	0	1	2	3	4	5	6	7
Values:	1			9				-

Fig. 4 GTS specification field

and accordingly modifies the value of queue state array in specified time intervals. This process only gives us a general estimation of the size of pending data and will not be accurate enough. Thus a second method is utilized in addition. To be more accurate in determining in determining the queue states, mechanism is needed by which nodes can inform coordinator of the number of their pending data. For this purpose the reserved bits in the standard data packet header have been used. The data packet header contains three reserved bits which can only provide eight different values. To declare a node's queue state in this limited space, these three bits are used as an eight-level meter which indicates the fraction of queue being occupied. Thus, each node gives the coordinator a more accurate description of its queue state. Each time a data packet is received the coordinator checks the queue state of the sending node and updates its corresponding array cell. After calculating network load state, the average channel utilization is calculated. This value is required for the algorithm to decide about the border between CSMA and TDMA[11]: Where num of used slots is the number of slots in active period in which a data packet has been sent or collision has occurred, num of collided slots is the number of contention access slots in the active period. Two factors can cause channel utilization to decrease: increasing collision and reduction of used slots. The first case shows that some data is accumulated in the nodes queues and their simultaneous effort for sending these data packets causes collision. In such a situation the coordinator checks the queue state array values and assigns TDMA slots to the nodes in descending order of their queue state values. Note that when a TDMA slots is assigned to a node, it will not send data in the CSMA/CA[10] period in the same beacon frame. Thus, number of nodes participating in the contention is decreased and fewer collisions occur. On the other hand, TDMA slots are only assigned to nodes having a queue state greater than or equal to one in order that under-utilization (which is a common problem in TDMA systems) does not happen. The second possible case which causes low channel utilization is the low number of used slots. In such a case a low number of collision[7] slots, shows that the network is in low load state and therefore few collisions have occurred. A long TDMA period could increase delay in such circumstances, because sending nodes have to wait until their TDMA slot arrives. Therefore when few slots are being used, the TDMA period length should be shortened so that end-to-end delay and the channel utilization through equation-3 do not descend because of time division access. Table 1 indicates the transmitter parameters for simulating the scenario.

TABLE 1
TRANSMITTER PARAMETERS

parameters	Value
Initial energy	12.1 joules
Transmit power	0.305 j
Receive power	0.395 j
Idle power	0.335 j
Packet rate	200 kb

5. Simulation Results

All simulations have been implemented using NS-2 simulator[10]

5.1 Energy consumption:

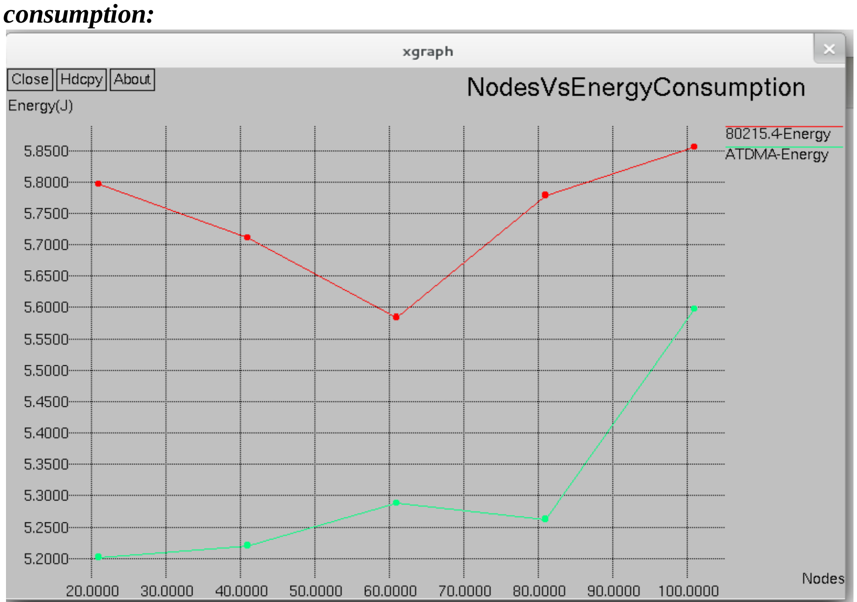

Fig. 5 Nodes v/s Energy consumption

The above graph shows that the ATDMA Energy consumption is very low compare to 802.15.4 with respect to the number of sources

5.2 End to end delay:

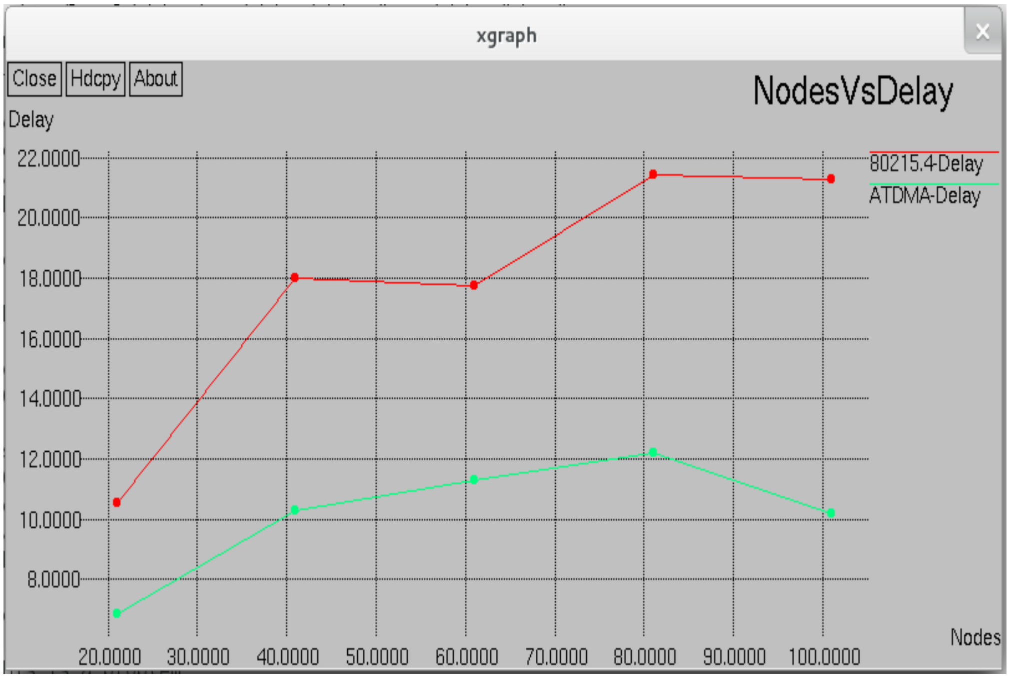

Fig. 6 Nodes v/s Delay

The above graph shows that the ATDMA Delay is very low compare to 802.15.4 with respect to the number of sources

5.3 Throughput:

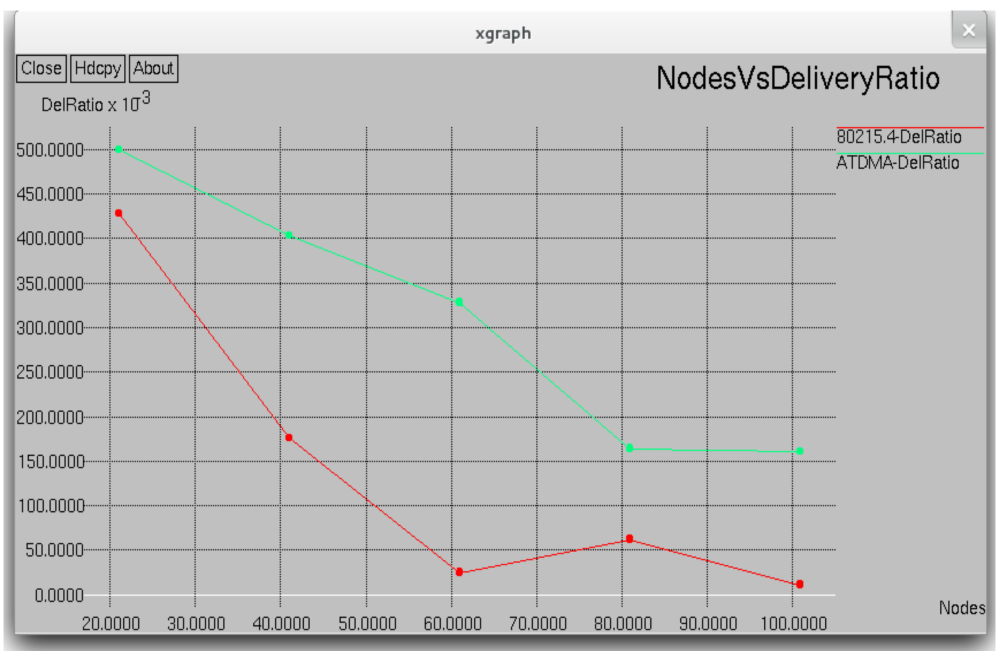

Fig. 7 Nodes v/s Delivery ratio

The above graph shows that the ATDMA throughput is very high compare to 802.15.4 with respect to the number of sources.

6. Conclusion

In this paper we have presented an adaptive CSMA/TDMA hybrid protocol based on 802.15.4 standard. The proposed protocol is practical in star topology and beacon enabled mode of the standard. Our hybrid method dynamically assigns a part of contention access period to TDMA and shares this period among nodes with high number of pending data. The network coordinator node takes advantage of a greedy algorithm to determine the border between CSMA/CA and TDMA periods. In order that energy consumption, rate delivery ratio and end to end delay of wireless sensor network are improved. Our simulations by NS-2 reveal that the CSMA/TDMA hybrid protocol considerably improves energy consumption and by both metrics performs better or equivalent to 802.15.4.we can compare our proposed protocol either Markov models or Skew ness/kurtosis for better significance.

7. References

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