Per-Sensor Energy-Saving MAC Protocol Design for Multi-hop Wireless Sensor Networks

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ABSTRACT
Multi-hop wireless sensor networks are mainly designed for environment monitoring. The lifetime of networks depends on the durability of the battery resource sensors, so it is crucial for sensors to efficiently use limited battery resource. The energy expends by sensor nodes in communication makes-up a quantum of their total amount of energy consumption. In existing research, most of the energy-saving MAC protocols reduce energy consumption by putting periodically sensors to sleep mode. Such a regular active/sleep schedule fails to adjust individual sensor node sleep duration according to per-sensor node communication traffic loads, which causes unnecessary idle listening problem and low power-efficiency. In this paper, we present an efficient energy-saving MAC protocol for saving energy in a multi-hop wireless sensor networks. This proposed protocol dynamically adjusts the active/sleep time duration of each sensor according to per-sensor node communication traffic load. Meanwhile, it can lead to much greater energy-efficiency by prolonging the sensor nodes sleeping duration, when in a network at per-sensor node communication traffic load is low. The basic idea of this proposed protocol is an analytical model for estimating the accurate per-sensor node communication traffic load in a multi-hop wireless sensor network and a grid-based quorum concept for regular active/sleep schedule.

Keywords
Multi-hop wireless sensor networks, per-sensor node traffic load, grid-based quorum, medium access control.

1. INTRODUCTION
Multi-hop wireless sensor networks (WSNs) have become an active research area for the researchers of this decade (2000-2010) due to their potential using range of applications in defence and scientific applications, wildlife habitat and environmental monitoring, industrial process monitoring and robotic exploration [1]. Multi-hop WSNs are consists of one or more battery-operated sensors with single chip embedded processor for processing, radio for wireless communication and small amount of memory. Usually, these sensors will have to work of their own with limited energy resources, once they deployed in hostile areas. Problem arise in multi-hop WSNs is that the lifetime of these multi-hop WSNs are limited because there lifetime is directly depend on lifetime of sensor. Energy consumption of sensors should be minimum because battery-powered is the only energy source to power these sensors, i.e. lower the energy consumption longer the lifetime of sensors/networks. Prolonging the lifetime of wireless sensors/networks is our first priority form all type of energy constrained in multi-hop WSNs because it is often not possible to recharge/replace the exhausted energy resources batteries of sensors. There is two ways to extend the lifetime of networks, one is hardware and other is software level. At hardware level most of the research is focused on improvements in the design of low-power and low-cost electronic sensor devices. In order to overcome the limitations in the hardware, researchers work at the software level in which energy-efficiency can be achieved through the design of various energy-efficient protocols. In a sensor node, there are three activities which are main sources of energy consumption in WSNs these are, (i) sensing unit, (ii) computation unit, (iii) radio operations unit [4]. Out of these, energy consume due to wireless radio operation for data transmission is the maximum one [2]. That is why the primary objective in multi-hop WSNs design is maximizing sensor/network lifetime, leaving the other metrics as secondary objectives. During communication sensor operate in four different states, transmit, receive, idle and sleep [3]. However, all the active states consume almost the same energy but the most energy is wasted during the idle state.

Energy conservation in communication can be performed in different layers of TCP/IP protocol suit, so researchers have focused on different layers to conserve energy more effectively. Energy conservation at Medium Access Control (MAC) layer is found to be the most effective by the researchers, due to its ability to control the wireless radio operations [4]. The MAC layer provides fine-grained control of the transceiver and allows switching the wireless radio on and off. How frequent and when such switching have to be performed is the major goal of an energy saving mechanism of the MAC layer. One functions of the MAC protocol is to avoid collisions from interfering sensor nodes. If we want to ensure for extend the lifetime of wireless communicating sensors, this can done by the using of good characteristics energy-saving MAC protocol. This idle MAC protocol reduces the power consumption of sensor and able to improve energy efficiency by maximizing sleep duration, minimizing idle listening and eliminating collision of packets. Almost there are various MAC protocols, but there is no standard energy-saving MAC protocol for multi-hop WSNs because multi-hop WSNs are application specific. In this paper, our objective to design an efficient energy-saving MAC protocol in which wake-up frequency of each and every sensor node purely determined according to per-sensor node communication traffic load.

2. PRELIMINARIES
2.1 Assumptions
In this paper, we made the following assumptions:

- Sensor nodes are randomly and uniformly distributed in a finite circular plane network region with the common sink situated at the centre.

- Each sensor node has a unique ID.
- All sensors have identical transceivers with same transmission range and wireless links are symmetric.
- Total Time is divided into a number of series time frames.
- All sensor nodes are static and time synchronized.
- All sensors generate their data packets with the same periodicity containing the sensed data and routes the data packet towards sink without data aggregation.
- The network is dense enough such that greedy routing always succeeds in finding a next hop node that advances the data packet towards the sink.
- Packet loss rate is q, uniform for all transmissions.

2.2 Problem Statement

There are various energy-saving MAC protocols for Multi-hop WSNs, S-MAC [5], T-MAC [6], D-MAC [7], Q-MAC [8] and TASL-MAC [9] protocols. These MAC protocols are not energy-efficient because there is number of limitations in these MAC protocols. Few MAC protocols (S-MAC, T-MAC, and D-MAC) are following the concept of regular active/sleep mechanism. Problem of sensors running in S-MAC, T-MAC, and D-MAC protocols is that they have to wake-up at every time frame to check if there is pending traffic or not, which is wastage of energy i.e. idle state. Since each sensor have different traffic loads means sensors that are closer to the sink are the heavy-loaded ones and all sensors adopting the same time frames to active/sleep are not energy-efficient. Where, other MAC protocols (Q-MAC and TASL-MAC protocols) which are able to adjust the sensors sleep duration according to their traffic loads. Problem is that the traffic load which is used is not calculated mathematically, it is just an assuming traffic load. Due to this, these MAC protocols are not purely adjust sensor active/sleep duration according to per-sensor node traffic loads. Therefore, there is need of an energy-efficient MAC protocol that able to adjust each sensor node active/sleep time frames determine according to actual mathematical calculated per-sensor node traffic loads.

3. PROPOSED PROTOCOL DESCRIPTION

In this section, we briefly introduce the grid-based quorum concept, calculation of per-sensor traffic load and finally, proposed per-sensor energy-saving MAC protocol.

3.1 Grid-Based Quorum Concept

A quorum is a request set that enables some actions if permission is granted. In this paper, a quorum set represents the time frames wherein a sensor must wake up. For non-quorum set, sensors are allowed to enter sleep mode for the entire time frame to conserve energy. Here grid-based quorums are used [10], therefore guarantee that any two sensors can wakeup and meet each other at some time frame.

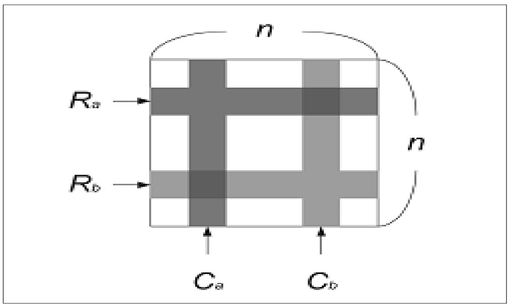

Fig 1: Example of Grid-Based Quorum

Fig. 1 shows, example of grid-based quorum in which n2 continuous time frames represented by an n × n grid [11]. In grid-based quorum, one row and one column are selected from an n × n grid as a quorum set for each sensor node. Quorum set select as, sensor A selects row Ra and column Ca as its quorum set, while sensor B selects Rb and Cb. In this way, we get the quorum set of each sensor in which a sensor must wake up. There are two intersections between sensors A and B, one at Ra and Cb and the other at Ca and Rb. It means that both sensors will wake up at intersection points.

3.2 Calculation of the Per-sensor node Traffic Load

In this paper, the traffic load of a per-sensor is defined as the average number of packets transmitted by the sensor at a distance during one time unit [12]. Fig. 2 shows a circular shaped network of radius l with the sink located at the centre.

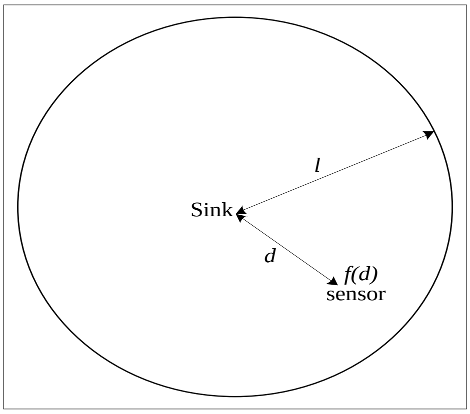

Fig 2: Example of Circular Shaped Plane Network Area

The traffic load of a sensor node located at a distance d from the sink during one time unit, f(d), is given by,

$$f(d) = \frac{S_t(d)}{\pi(2d+\varepsilon)\varepsilon\rho} \cdot \frac{1}{1-q}$$

where St(d) is given by,

$$S_t(d) = \begin{cases} \pi(2d+\varepsilon)\varepsilon\rho & if\ d = l, \\ \pi(2d+\varepsilon)\varepsilon\rho + \sum_{i\varepsilon(d,l]} P_{i,d} S_t(i) & if\ 0 < d < l, \end{cases}$$

and $P_{i,d}$ denotes state transition probability for radio model. Based on this $P_{i,d}$, we can calculate the accurate traffic loads incurred at the individual sensors. $P_{i,d}$ for the ideal and log normal radio model have been derived in [12]. Here, $S_t(d)$ is a recursive function. Since, we know $S_t(l)$, the initial value of $S_t(d)$, we can calculate $S_t(l–\varepsilon)$ according to Equation (2). Similarly, $S_t(l-2\varepsilon)$ and so on derived. Finally, for any given d, $S_t(d)$ can be computed, which we can calculate f(d) using Equation (1) [12]. Note that, Equation (1) derives the traffic load of all sensors excluding the common sink because the sink exclusively acts as a receiver. Hence, the traffic load of the sink is zero. The symbols used are listed in Table 1 [12].

Finally, we know the exact traffic load of per-sensor node in multi-hop WSNs. Now with the help mathematical calculated traffic load we select the accurate grid size of each sensor. As a result, it increases the sleep duration of each sensor by which we save a lot of energy wastage in idle state.

Table 1. List of symbols used in calculation

Symbol	Definition
ε	Quantization interval
ρ	Node density, i.e. the number of nodes per unit area
i, j, d	Euclidean distance from a sensor to the centrally located sink
Pi,d	State transition probability, i.e. the probability that a sensor at distance i from the sink can forward its packets to the sensor at distance d

3.3 Proposed Per-Sensor Energy-Saving MAC Protocol

In our proposed MAC protocol, we select accurate grid size of sensor purely according to its communication per-sensor node traffic load (PSTL), which is calculated mathematically. The idea behind proposed MAC protocol is to increase a sensor's grid size, in order to prolong its sleep duration when its traffic load is light, and to decrease its grid size, making it wake up more frequently, when its traffic load is heavier. In our protocol, to facilitate implementation, we defined four (may be more, user depended) traffic load thresholds, Threshold1, Threshold2, Threshold3, and Threshold4, which mean five grid sizes can be selected for the sensors in proposed MAC protocol as shown below [13]:

If PSTL ≥ Threshold1, we select 1×1 grid size,

If Threshold1 ≥ PSTL ≥ Threshold2, we select 2×2 grid size,

If Threshold2 ≥ PSTL ≥ Threshold3, we select 3×3 grid size,

If Threshold3 ≥ PSTL

≥ Threshold4, we select 4×4 grid size,

and If Threshold4 ≥ PSTL, we select 5×5 grid size.

According to our scenario, the latency increased dramatically when every sensor's packet arrival rate exceeded, say's 12 Kbps [13]. We considered the network environment to be overloaded when each sensor traffic load was more than 12 Kbps; thus, we set grid size to 1 × 1 when its traffic load exceeded 12Kbps. That is, we set Threshold1 to be 12 Kbps. The number of thresholds and their values can adjust according to different per-sensor traffic loads.When the per-sensor traffic load decreases, a sensor's wake-up time frames should also be reduces. Thresholds Threshold2, Threshold3 and Threshold4 are define as being proportional to the wake-up frequency, when compared to a 1×1 grid size [13]. In an n × n grid, for each sensor we select 2n-1 time frames among the total number of n2 time frames as the quorum set. That is, a sensor with a grid size of n × n wake-up at the fraction of (2n-1)/n2, compared to a sensor with a 1×1 grid size. When a sensor's packet arrival rate is reduced to (2n-1)/n2, when compared to being overloaded, we should also increase its grid size to n × n; this implies

sensor with large grid size, therefore sensor with small grid size have intersections during sensor with large grid size quorum group

$$Threshold_2 = 12 \times \frac{2 \times 2 - 1}{2^2} = 12 \times \frac{3}{4} = 9Kbps$$

$$Threshold_3 = 12 \times \frac{2 \times 3 - 1}{3^2} = 12 \times \frac{5}{9} = 6.67Kbps$$

$$Threshold_4 = 12 \times \frac{2 \times 4 - 1}{4^2} = 12 \times \frac{7}{16} = 5.25Kbps$$

With these settings, a sensor can select the best grid size, purely according to per-sensor node traffic load, in order to achieve most efficient energy conservation MAC protocol. Also, the grid allocation rules must still be followed and with legal grids, two sensors with different grid size will intersect with each other [13]. Means, sensor with small grid size wakes up more frequently than

4. CONCLUSION

In our research, we attempt to find out and overcome limitations of the multi-hop WSNs such as: limited energy resources, lower power-efficiency, and higher transmission latency. We study various energy-saving MAC protocols for Multi-hop WSNs. In future we will compare the performance of various protocols in terms of alive nodes, latency, power consumption, successful delivery ratio and signaling overhead with our proposed MAC protocol. Finally, we will successfully propose an efficient per-sensor energy-saving MAC protocol for prolonging the lifetime of WSNs.

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