TA-MAC: Task Aware MAC Protocol for Wireless Sensor Networks

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***Abstract*— In wireless sensor networks (WSNs), reducing energy consumption of resource constrained sensor nodes is one of the most important issues. In this paper, we propose a task aware (TA) MAC protocol, which improves energy efficiency and throughput by introducing a channel access scheme depending on traffic load in WSNs. The amount of traffic load of a sensor node can be estimated by its task activity, where a task is an operation that the sensor node performs based on the schedule set by data dissemination procedures in advance. In addition, the sensor node collects neighbor nodes' task activities and determines its channel access probability using the collected information. Consequently, the sensor node can choose a more suitable channel access probability which is adaptive to its traffic load as well as neighbor's traffic load. We carry out performance analysis using a p-persistent MAC protocol. The results reveal that the TA-MAC protocol exhibits less collisions than the normal p-persistent MAC protocol and thus it achieves energy efficient operations. Also, it can been seen that the TA-MAC protocol improves system throughput compared with other protocols.**

I. Introduction

Wireless sensor networks (WSNs) is a core technology to realize future ubiquitous computing environment. Potential WSN applications include intrusion detection in home, target tracking in battlefield, habitat monitoring, climate control, disaster management, etc. Since WSNs have quite different characteristics from the existing wired network (e.g., Internet), extensive studies have been conducted in the area of WSNs [1]. Specifically, handware/software architecture for wireless sensor nodes, routing/medium access control (MAC) protocol, data aggregation, cluster formation have been extensively investigated in the literature.

Even if all of these researches consider different problems, they share a common design issue, i.e., *energy efficiency*. Typically, wireless sensor nodes are implemented as a small-size and resource-constrained device. This is because the main mission of wireless sensor nodes is to gather some information of interest from physical worlds. To this end, a large number of small-sized sensor nodes are distributed in a large geographical area. In such a deployment scenario, it is not expected to recharge the power of sensor nodes. Accordingly, wireless sensor nodes should be able to prolong their lifetime within the limited energy budget.

For energy efficient operations, many studies have been conducted. The focus of this paper is energy efficiency in MAC protocols. In MAC protocols, there are three main sources for energy waste: *collision*, *overhearing*, and *idle sensing* [2]. Typically, since a wireless channel is shared by multiple nodes, a collision occurs when more than two nodes try the packet transmission simultaneously. The collision increases energy consumption as well as packet delivery latency. The second source is overhearing, which means that a node picks up packets that are destined to other nodes. This is because it is difficult whether the packet is destined for other nodes or itself in a shared wireless channel. The last source is idle listening, i.e., listening to receive possible traffic while the node is idle state. Idle listening becomes more worse in WSNs, where there exist a number of nodes that are not involved in data routing.

To mitigate the effects of these energy sources, several MAC protocols have been proposed. These protocols can be classified into two classes: *polling-based* and *contention-based*. Self-organizing MAC for sensor networks (SMACS) [6] and traffic adaptive medium access (TRAMA) [7] belong to the polling-based MAC protocol. In addition, a TDMA-based protocol is proposed in [8]. The polling-based protocol is naturally contention free, so that it can reduce the energy waste incurred by channel collisions. However, it is not an easy task to set a polling schedule or to assign time slots to sensor nodes.

Accordingly, contention-based protocols are more prevalent in WSNs. The most representative one is sensor MAC (S-MAC) [2]. S-MAC enables low duty cycle operation and the formation of virtual clusters based on common sleep schedules, in order to reduce control overhead and enable traffic-adaptive wake-up. Also, S-MAC employs message passing to reduce contention latency of long messages. In [3], an adaptive duty cycle is exploited and timeout MAC (T-MAC) is proposed. Similarly, an adaptive scheduling of duty cycle based on traffic load is introduced in [4]. However, all of them assume a carrier sense multiple access/collision avoidance (CSMA/CA) style contention resolution algorithm.

The CSMA/CA algorithm defers the channel access (i.e., *backoff*) when a collision occurs. The amount of backoff is determined by a uniform distribution of [0, contention window]. More details can be found in [9]. Unfortunately, this backoff algorithm is not energy efficient. This is because each node has the same channel access probability in this algorithm regardless of its activity. A well known analysis in [10] reveals that the optimal channel access probability maximizing throughput (or minimizing collisions[1]) is dependent on the network load. Specifically, the optimal channel access probability is inversely proportional to the network load.

In this paper, we propose a task aware MAC (TA-MAC) protocol for WSNs. The main idea is to adjust the channel access probability depending on a sensor node's and its neighbor nodes' traffic load. In typical internet access services, it is quite difficult to estimate traffic loads in advance, due to diversity and heterogeneous of Internet applications. However, sensor nodes in WSNs are designed to perform a special task and the task information is propagated to sensor nodes in advance by data dissemination protocol. Consequently, the proposed idea can be easily implemented in WSNs in combination with data dissemination protocols. By choosing a suitable channel access probability depending on traffic load, TA-MAC can achieve high throughput as well as low energy consumption.

The remainder of this paper is organized as follows. In Section II, a simple data dissemination model is described. The task-aware MAC protocol is presented in Section III. The TA-MAC is modeled analytically and evaluated numerically in Sections IV and V, respectively. Section VI concludes this paper.

II. Data Dissemination Model

Most WSN applications, especially surveillance monitoring systems, are based on a *publish/subscribe mechanism* [13].

Figure 1 illustrates the *subscribe* phase. An entity (i.e., sink node) registers its interest with WSNs. The interest can include various information regarding events of the interest, e.g., data type, interval, region, and start/end time. This information varies depending on application types. However, time-related information describing subscription interval and period is necessary for most applications. The TA-MAC protocol utilizes the time-related information to adjust the channel access probability, which will be elaborated in Section III. The *publish* phase is depicted in Figure 2. Sensor nodes deployed in WSNs monitor some information from physical world and a sensor node (i.e., source node) detecting an event delivers the interesting information to the sink node.

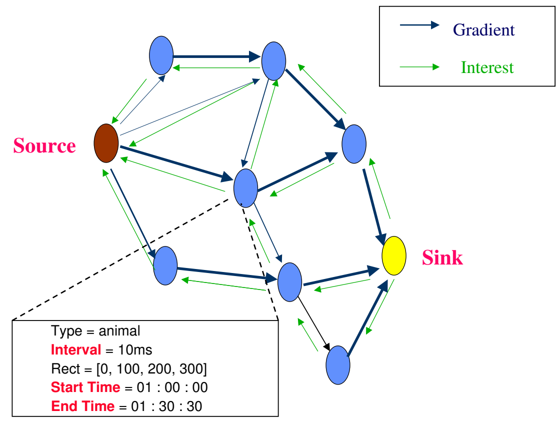


Fig. 1. Subscribe phase.

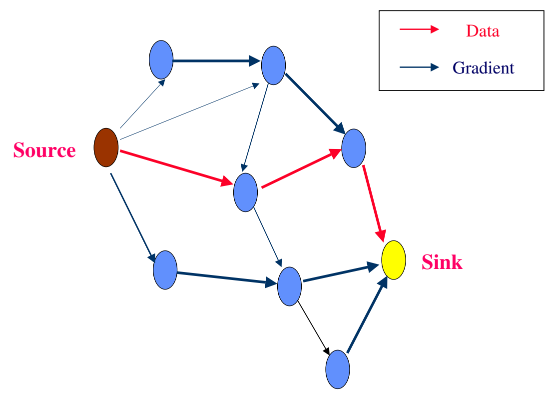


Fig. 2. Publish phase.

III. TA-MAC: Task Aware MAC Protocol

The TA-MAC protocol consists of two procedures: *task monitoring* and *collaborative adjusting*. A sensor node first monitors its task activity that the node is involved and estimates the transmission attempt rate. The transmission attempt rate represents the frequency that the sensor node tries to access the channel per unit time. Since the optimal channel access probability is also dependent on the network load, the sensor node adjusts its channel access probability through the collaboration with neighbor nodes.

A. Task Monitoring

As mentioned before, the TA-MAC protocol utilizes the time-related information available from the data dissemination model. Let D_j and T_j be the duration and interval of a task j. Then, the transmission attempt rate of the task j during D_j is given by $1/T_j$. Since a sensor node can be involved in multiple tasks, the total transmission attempt rate of the sensor node i at a given time t is given by

$$r_i(t) = \sum_j 1/T_j, \tag{1}$$

where j is the index of tasks that are active at time t.

The total transmission attempt rate varies as a new task is triggered or the existing task is terminated. Figure 3 shows an illustrative example for task monitoring. At $[t_0,t_1]$, there is only task 1. Therefore, the total transmission attempt rate, $r_i(t)$, is $1/T_1$. At t_1, a new task 2 is started and then $r_i(t)$ is set to $1/T_1 + 1/T_2$ during $[t_1,t_2]$. $r_i(t)$ is changed to $1/T_2$ when the task 1 is finished at t_2.

[1]In a collision-based MAC protocol, reducing collisions achieves low channel access latency and energy consumption

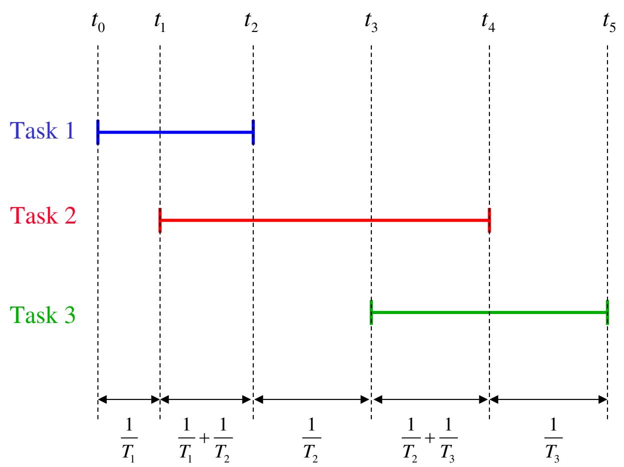


Fig. 3. An example of task monitoring

B. Collaborative Adjusting

With the task monitoring procedure, a sensor node can determine its total transmission attempt rate. However, the total transmission attempt rate cannot be converted into the channel access probability directly. This is because the total transmission attempt rate does not consider other nodes' total transmission attempt rates (or traffic loads). To determine the channel access probability considering other nodes' activity, the other collaborative adjusting comes into play.

In the collaborative adjusting procedure, a sensor node periodically exchanges the locally calculated total transmission attempt rate with its neighbors. The message exchange can be accomplished by a Hello protocol or a schedule exchange protocol in S-MAC. Eq. (2) shows the channel access probability at time t using its own and neighbors' total transmission attempt rates. Namely, the channel access probability of a node is proportional to its total transmission attempt rate whereas inversely proportional to the sum of neighbor's total transmission attempt rates (including the node itself).

$$p_i(t) = \frac{r_i(t)}{\sum_k r_k(t)}. \tag{2}$$

Of course, the exchanged message can be lost by channel collisions or link errors. In that case, the sensor node determines its channel access probability using the successfully received messages during a pre-defined time period.

IV. Performance Analysis

To evaluate the performance of the TA-MAC protocol, we apply the mechanisms of the TA-MAC protocol to p-persistent CSMA protocol[2]. Figure 4 illustrates the system model consisting of n nodes. We assume that time is slotted and each successful transmission or collision occupies one time slot. In the p-persistent CSMA protocol, each node tries to access a wireless channel with the probability of p in a given time slot. In most works [10], [11], [12], saturated nodes, i.e., they are always ready to send data, are assumed for tactical analysis. This is because it is quite difficult to build a reasonable traffic model in diverse Internet access environments. On the other hand, in WSNs, each node performs its role based on the task that is disseminated in advance. Accordingly, it is safely assumed that the channel access probability is related to the pre-assigned tasks.

Let r_i be the total transmission attempt rate of node i in a given time slot, which is dependent on the task activity. Then, the channel access process at a given time slot of node i can be modeled as a Poisson process with rate r_i. Hence, the channel access probability of node i is given by

$$p_i = 1 - e^{-r_i}. \tag{3}$$

Using Eq. (3), the probability that the transmission of node i succeeds is expressed by

$$P_i^{Succ} = p_i \cdot \prod_{j \neq i} (1 - p_j). \tag{4}$$

Then, the expected number of time slots until the transmission of node i is successful, i.e., the expected delay experienced by node i, $E_i(D)$, is given by Eq. (5). Here, the size of a time slot is normalized to unity.

$$E_i(D) = \sum_{n=1}^{\infty} n \cdot (1 - P_i^{Succ})^{n-1} \cdot P_i^{Succ} = \frac{1}{P_i^{Succ}}. \tag{5}$$

On the other hand, the expected throughput, $E(T)$, is given by Eq. (6). the packet size is also normalized to unity. Note that only one node can transmit a packet at a time slot. Therefore, P_i^{Succ} is a mutually independent probability.

$$E(T) = \sum_i P_i^{Succ}. \tag{6}$$

V. Numerical Results

For numerical analysis, we assume a simple network model where 5 nodes share a wireless channel. To show the effect of different total transmission attempt rates, we consider four cases. Table I show the different total transmission attempt rates of individual 5 nodes. In cases 1 and 2, each node has the same total transmission attempt rate. However, the total transmission attempt rate in case 2 is higher than that in case 1. In case 3, the total transmission attempt rate increases linearly, whereas the total transmission attempt rate increases exponentially in case 4.

We evaluate the performance of the TA-MAC protocol against two different p-persistent CSMA protocols. First protocol is a normal p-persistent CSMA protocol, which determines p using Eq. (3), but no knowledge about neighbor nodes

[2]However, the TA-MAC protocol can be applied to other types of MAC protocols, e.g., the CSMA/CA protocol in the IEEE 802.15.3/4 standard [14], [15].

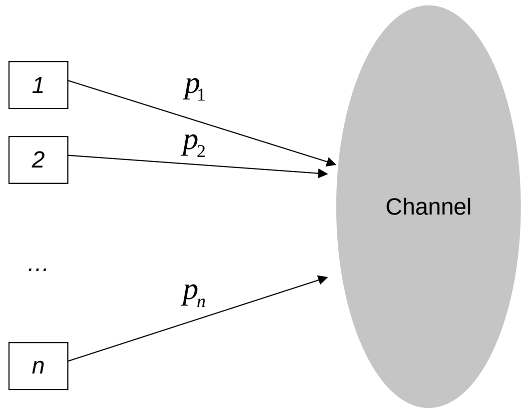


Fig. 4. System Model

TABLE I
FOUR DIFFERENT CASES OF TOTAL TRANSMISSION ATTEMPT RATES (r_i).

Case	node 1	node 2	node 3	node 4	node 5
1	0.1	0.1	0.1	0.1	0.1
2	1.0	1.0	1.0	1.0	1.0
3	0.1	0.3	0.5	0.7	0.9
4	0.1	0.2	0.4	0.8	1.6

is used. Second protocol is a uniform p-persistent CSMA protocol, which p is set to $1.0/n$ where n is the number of contending nodes. On the other hand, as described before, the TA-MAC protocol sets p using Eq. (2).

Figure 5 shows each node's average delay in four different cases. A small average delay represents that the node experiences less channel collisions and hence higher energy saving is achieved. In cases 1 and 2, since the total transmission attempt rate is identical for each node, there is no difference between each node's average delay, and the TA-MAC protocol shows the same performance as the uniform p-persistent CSMA protocol. However, as shown in Figures 5(a) and (b), the TA-MAC protocol shows a less average delay than the normal p-persistent CSMA protocol. The improvement of the TA-MAC protocol is more clear when the total transmission attempt rate is high, i.e., case 2. Namely, in case 2, since all nodes have higher total transmission attempt rates, they try to access the shared channel more aggressively. Therefore, more collisions happen and these collisions result in a longer average delay.

As shown in Figures 5(c) and (d), in the TA-MAC and normal p-persistent MAC protocols, a node with a higher total transmission attempt rate (e.g., node 5) has a less average delay when total transmission attempt rates are different among nodes. On the contrary, the uniform p-persistent exhibits the constant average delay. Apparently, the TA-MAC protocol reduces the average delay compared with the normal p-persistent MAC protocol. The significance of the TA-MAC protocol against the normal p-persistent MAC protocol becomes more clearer as the skewness of the total transmission attempt rates, i.e., the improvement of the TA-MAC protocol is more remarkable in Figure 5(d). Compared with the TA-MAC protocol, the uniform p-persistent MAC protocol shows a less average delay for nodes with low transmission attempt rates. This is because the uniform p-persistent MAC protocol guarantee the same channel access probability regardless of transmission attempt rate. However, it increases the average delay of nodes with high transmission attempt rates and it has an undesirable effect on the maximization of channel throughput, which will be elaborated with Figure 6 in later.

As shown in Eq. (7), the energy consumption of node i can be represented by a function of the expected delay of the node.

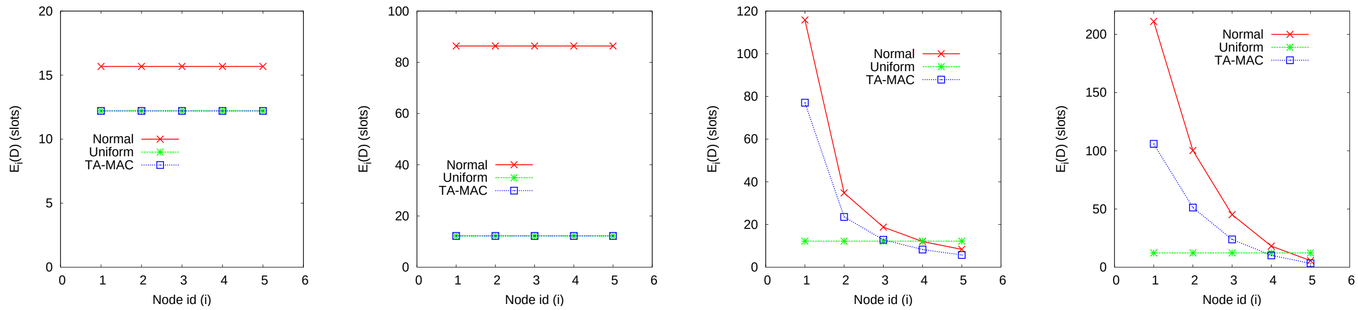
$$\begin{aligned} E_i(C) &= \sum_{n=1}^{\infty} ((n-1)E_i + E_b) \cdot (1 - P_i^{Succ})^{n-1} \cdot P_i^{Succ} \\ &= E_i \times \frac{1}{P_i^{Succ}} + E_b - E_i = E_i(D) \cdot E_i + E_b - E_i, \end{aligned} \tag{7}$$

where E_b and E_i are energy consumptions in the busy and idle time slots, respectively. Accordingly, it is concluded that the TA-MAC protocol can reduce the energy consumption compared with the normal p-persistent protocol from Figure 5.

Figure 6 illustrates the average normalized throughput. In both cases 1 and 2, the throughputs of the TA-MAC protocol and uniform p-persistent MAC protocol are the same, i.e., 0.4096. However, the throughput of the normal p-persistent MAC protocol is significantly reduced from 0.3189 in case 1 to 0.05789 in case 2. This because the normal p-persistent MAC protocol tries to access the channel without any neighbor information. Therefore, when overall transmission attempt rates are high (i.e., case 2), the normal p-persistent MAC protocol incurs a large number of collisions and degrades the throughput. The TA-MAC protocol shows higher throughput than the the normal p-persistent and uniform MAC protocols in all cases. As described before, in the uniform p-persistent MAC protocol, nodes with low transmission attempt rates show less average delay, at the expense of increasing average delay of nodes with high transmission attempt rates. This is not desirable because it prohibits the throughput enhancement that can be achieved when nodes with high transmission attempt rates have higher channel access probabilities. On the contrary, since the TA-MAC protocol gives higher channel access probabilities to nodes with high transmission attempt rates, the throughput can be significantly improved. In short, the throughput gain of the TA-MAC is more remarkable when the overall transmission rates are high (i.e., case 2) or the skewness among transmission rates is sharp (i.e., case 4).

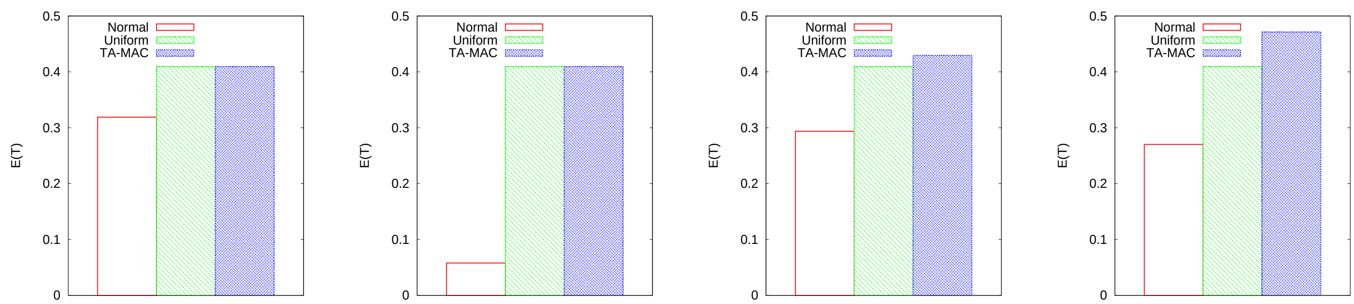
VI. CONCLUSION

In this paper, we proposed a task aware MAC protocol for WSNs. As a kind of cross layering approach, the TA-MAC protocol determines the channel access probability depending on a node's and its neighbor nodes' traffic loads through the interaction with the data dissemination protocol. Our analysis results reveal that the TA-MAC protocol can reduce



(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

Fig. 5. Average channel access latency ($E(D)$).



(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

Fig. 6. Average throughput ($E(T)$).

energy consumption and improve the throughput by eliminating unnecessary collisions. The TA-MAC protocol is feasible because it can be integrated with other energy efficient MAC protocol (e.g., SMAC). This is because the TA-MAC protocol focuses on the determination of channel access probability that is orthogonal to the previous MAC protocols for WSNs. As our future work, we will evaluate the performance of the TA-MAC protocol in more diverse environments.

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