Application Aware Data Aggregation in Wireless Sensor Networks

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***Abstract*— In wireless sensor networks (WSNs), data aggregation schemes have been extensively investigated in order to reduce energy and bandwidth consumptions. In this paper, we propose an application-aware data aggregation (AADA) scheme, which applies different aggregation policies adaptively, depending on the types of packets (i.e. real-time (RT) and non real-time (NRT) packets). Specifically, NRT packets wait at a queue until the number of accumulated packets is equal to the maximum aggregation limit. On the other hand, RT packets, which are sensitive to the aggregation latency, are transmitted as soon as possible without any waiting at the queue. We develop an analytical model to evaluate the AADA scheme in terms of the average aggregation degree and aggregation latency. The numerical results show the energy saving gain and the effects of the arrival rate of RT packets and the aggregation threshold.**

I. INTRODUCTION

It is envisioned that wireless sensor networks (WSNs) will bring about a new paradigm for ubiquitous computing. WSNs consist of hundreds or even thousands of resource-constrained nodes and these nodes are required to function for extended time period. Potential WSN applications include intrusion detection, target tracking, disaster management, habitat monitoring, etc.

Since WSNs have quite different characteristics from the existing wired network (e.g. Internet), extensive studies have been conducted in a variety of areas [1], e.g. hardware/software architectures [2], data dissemination [3], medium access control (MAC) protocol [4], ad-hoc networking [5], data aggregation [6], and power conservation [7].

As mentioned before, wireless sensor nodes are highly resource constrained, so that it is a key issue to prolong their lifetime by reducing energy consumption. One of the most important energy saving mechanism is to exploit *data aggregation*. In WSNs, the raw sensed data is typically forwarded to a sink node for further processing. The key concept of data aggregation is to eliminate unnecessary packet transmission by filtering out redundant sensor data and/or by performing an incremental assessment of the semantic of the data. Also, data aggregation reduces the number of wireless channel contention and transmission overhead. In so doing, it achieves an energy-efficient data dissemination in WSNs.

Two representative aggregation schemes are the application dependent data aggregation (ADDA) scheme [3] and the application independent data aggregation (AIDA) scheme [8]. The ADDA scheme performs aggregations based on the application context as a data centric protocol, while the AIDA scheme separates aggregation decisions from the application context. When a specific target application is given, the ADDA scheme may be a better choice. However, the current ADDA scheme does not differentiate real-time (RT) and non real-time (NRT) packets.

In some WSN applications, real-time delivery is an important design consideration. Let us take a fire detection system. Monitored data in normal state are collected without any delay constraints and the data will be delivered in an energy-efficient manner. On the other hand, the data indicating emergency (i.e. fire) should be delivered as soon as possible. In this case, real-time delivery rather than energy efficient delivery would be appreciated. In addition, in a habitat monitoring system [9], a query can be specified as “Report the average temperature in the region A within D time units with a interval of T time units”. When this query is processed, timely delivery of sensed data should be firstly considered rather than energy efficiency. Consequently, in these applications, data aggregation should be carefully performed not violating the real-time delivery constraints.

However, as indicated in [10] and [11], there exists a trade-off between energy saving due to data aggregation and delay for real-time delivery. In other words, as more data are aggregated, a higher energy saving is achieved. However, it results in a longer delivery latency. To balance energy saving and delay, a scheduling algorithm, which is based on weighted fair queueing (WFQ), is employed in [10]. In [11], algorithms minimize the energy consumption in data aggregation tree while meeting the given delay constraint.

In this paper, we propose an *application aware data aggregation (AADA)* scheme, which is an enhanced version of ADDA. Unlike the ADDA scheme, the AADA scheme adjusts the aggregation degree[1] depending on the data types, i.e. RT and NRT packets. In general, the NRT packets are less sensitive to the delivery latency caused by data aggregation. Therefore, the NRT packets can wait at a queue until the number of accumulated packets is equal to the maximum aggregation limit. On the other hand, the RT packets are sensitive to the aggregation latency, so that the RT packets

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[1] The aggregation degree is defined as the number of packets aggregated into a single transmission packet

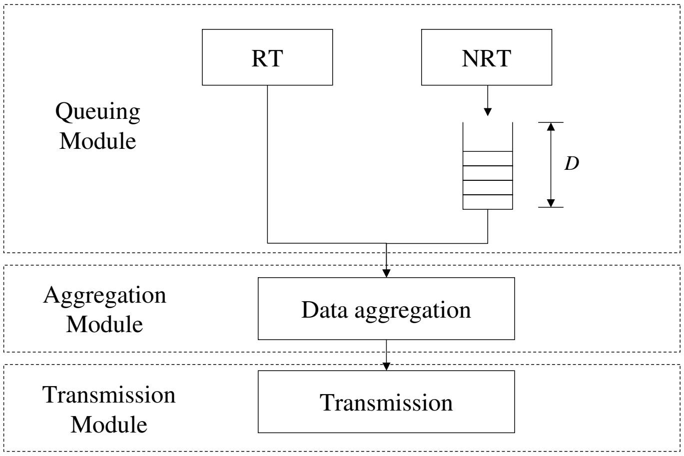

Fig. 1. Application Aware Data Aggregation.

should be transmitted as soon as possible. In short, the AADA scheme enables to efficiently aggregate RT and NRT packets while meeting application's delay requirements. Unlike [10] and [11], the AADA scheme does not require any complex algorithms for packet transmission or optimization problem. Therefore, the AADA can be easily implemented in resource-constraint sensor nodes.

The remainder of this paper is organized as follows. In Section II, an application aware data aggregation (AADA) scheme is introduced. In Section III, we present an analytical model to evaluate the average aggregation degree and the average aggregation latency. Section IV shows numerical results and Section V concludes this paper.

II. APPLICATION AWARE DATA AGGREGATION (AADA)

A. Overview

Figure 1 shows the basic diagram of the AADA scheme. The AADA scheme deals with RT and NRT packets differently. In the case of the RT packet, it should be delivered as quickly as possible. On the other hand, the NRT packet is less sensitive to the delivery latency.

The AADA scheme consists of three modules: *queuing*, *aggregation*, and *transmission*. In the queuing module, a FIFO (First Input First Output) queue with a size of D is employed for NRT packets. We assume that D NRT packets can be accumulated without significant violation of application's delay requirements. The RT packets are delivered to the aggregation module without any queueing. On the contrary, the NRT packets are first queued in the queueing module. The NRT packets accumulated in the aggregation queue are flushed when the queue is full (i.e. the queue size becomes D) or an RT packet arrives. In the most link layer technologies (e.g. IEEE 802.11), the maximum service data unit (SDU) length for the aggregated packets is specified. For example, the maximum MAC SDU size in the IEEE 802.11 specification is 2304 bytes [13]. Accordingly, D should be set by considering the maximum SDU length at the lower layer.

At the data aggregation module, RT and NRT packets can be aggregated into a single packet, dubbed an aggregation packet (or transmission packet). The number of the aggregated packets depends on how soon an RT packet arrives. Namely, an aggregation packet is composed of zero or one arrived RT packet and zero or multiple NRT packets that have been accumulated in the aggregation queue. Therefore, the length of the aggregation packet (L_A) is bounded as follows.

$$L \leq L_A \leq D \cdot L,$$

where L is the length of a RT or NRT packet. We assume that the lengths of RT and NRT packets are identical. The aggregation packet is then transmitted to the next hop through the transmission module via broadcast. Then, multiple destination nodes receive the packet by utilizing promiscuous mode at the MAC layer [12].

B. Determination of D

In the AADA scheme, D is a key parameter to determine energy saving and latency[2]. Therefore, D should be carefully set depending on the latency constraint and energy consumption. Apparently, as D increases, the data aggregation latency becomes large. On the contrary, the energy consumption decreases as D increases. Accordingly, the determination of D is formulated as an optimization problem.

$$\begin{array}{ll} \text{Minimize} & Energy(D) \\ \text{Such that} & Latency(D) \leq Constraint \end{array}$$

where $Energy(D)$ and $Latency(D)$ represent the energy consumption and latency due to data aggregation with D. $Constraint$ is a given latency constraint. Using an analytical model presented in Section III, this optimization problem can be resolved by a simple binary search algorithm [14]. We will elaborated the effect of D in Section IV.

III. ANALYTICAL MODEL

We evaluate the AADA scheme in terms of the *aggregation degree* and *aggregation latency*. The aggregation degree refers to the number of aggregated packets within an aggregation packet. The aggregation degree is determined by the aggregation threshold (D) and the RT packet arrival rate. The higher the aggregation degree is, the higher energy saving by aggregation can be achieved. On the other hand, the aggregation latency is defined as an interval between two consecutive transmissions of aggregation packets. In other words, the aggregation latency is the average time period between two consecutive transmissions in the AADA scheme, i.e. the queueing latency. As mentioned before, the AADA scheme transmits a packet when the RT packet arrives or the number of accumulated NRT packets reaches D.

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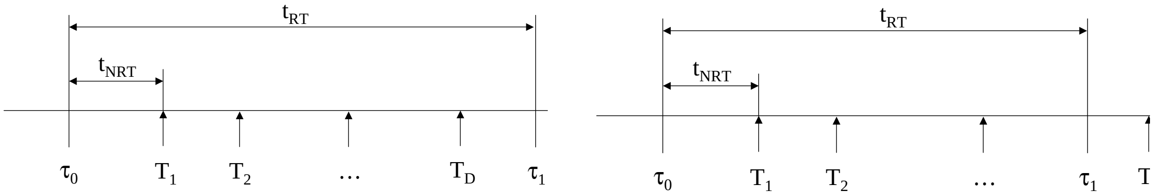
[2] In the AADA scheme, no sooner had RT packets arrived than they are transmitted, i.e. there is no aggregation latency for RT packets. Therefore, the latency is a performance metric for NRT packets



(a) Case 1

(b) Case 2

Fig. 2. Timing diagram

Figure 2 illustrates two cases for analytical modeling. In Figure 2, RT packets arrive at τ_0 and τ_1, and T_i denotes the time epoch when the i-th NRT packet arrives. In Figure 2(a), before the next RT packet arrives, D NRT packets arrive. Therefore, D NRT packets are aggregated into one aggregation packet. On the contrary, an RT packet arrives before D NRT packets arrive in Figure 2(b). Accordingly, the AADA scheme transmits the aggregation packet at τ_1.

Typically, a RT packet is generated by an event of interest (e.g. fire event in a fire detection system). Therefore, the generating process of RT packets can be modeled by a Poisson distribution. On the other hand, a NRT packet can be generated by an event or periodically. Hence, we consider these two cases: non periodical NRT packet and periodical NRT packet.

A. Non Periodical NRT Packet

Eq. (1) shows the average aggregation degree when the inter-arrival time (t_{RT}) of RT packets is given. The first term represents the case 1 (see Figure 2(a)), while the second term refers to the case 2 (see Figure 2(b)).

$$\begin{aligned} E(N|t_{RT}) &= \Pr(n \geq D|t_{RT}) \cdot D \\ &+ \sum_{i=0}^{D-1} \Pr(n = i|t_{RT}) \cdot (i+1), \end{aligned} \tag{1}$$

where n is the number of NRT packets that have arrived during t_{RT}. Since it is assumed that the NRT arrival process follows a Poisson distribution with a rate of λ_{NRT}, $\Pr(n = i|t_{RT} = \tau)$ is given by

$$\Pr(n = i|t_{RT} = \tau) = \frac{e^{-\lambda_{NRT}\tau} \cdot (\lambda_{NRT}\tau)^i}{i!}. \tag{2}$$

We assume that the inter-arrival process of RT packets follows an exponential distribution with a mean of $1/\lambda_{RT}$. Hence, by integrating Eq. (1) in $[0, \infty]$, the average aggregation degree ($E(N)$) is given by

$$\begin{aligned} E(N) &= \int_0^\infty E(N|t_{RT}) \cdot f_{RT}(\tau) \cdot d\tau \\ &= \int_0^\infty E(N|t_{RT}) \cdot \lambda_{RT} e^{-\lambda_{RT}\tau} \cdot d\tau. \end{aligned} \tag{3}$$

Likewise, the average aggregation latency when the RT inter-arrival time is given, is calculated as

$$\begin{aligned} E(L|t_{RT}) &= \Pr(n \geq D|t_{RT}) \cdot D \cdot \frac{1}{\lambda_{NRT}} \\ &+ \sum_{i=0}^{D-1} \Pr(n = i|t_{RT}) \cdot \frac{1}{\lambda_{RT}}. \end{aligned} \tag{4}$$

Then, the average aggregation latency, $E(L)$, is given by

$$\begin{aligned} E(L) &= \int_0^\infty E(L|t_{RT}) \cdot f_{RT}(\tau) \cdot d\tau \\ &= \int_0^\infty E(L|t_{RT}) \cdot \lambda_{RT} e^{-\lambda_{RT}\tau} \cdot d\tau. \end{aligned} \tag{5}$$

B. Periodical NRT Packet

In the case of periodical NRT packet, the number of NRT packets when t_{RT} is given is expressed as $\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor$, where T_{NRT} is the interval of the periodical NRT packet. If $\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor$ is larger than D, the average aggregation degree is D; otherwise, the average aggregation degree is $max\{1, \lfloor \frac{t_{RT}}{T_{NRT}} \rfloor\}$. Therefore, $E(N|t_{RT})$ is given by

$$\begin{aligned} E(N|t_{RT}) &= D \cdot \delta(\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor) \\ &+ max\{1, \lfloor \frac{t_{RT}}{T_{NRT}} \rfloor\} \cdot (1 - \delta(\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor))). \end{aligned} \tag{6}$$

In Eq. (6), $\delta(\cdot)$ is defined as follow:

$$\delta(t) = \begin{cases} 1 & t > D \\ 0 & otherwise \end{cases}$$

Then, $E(N)$ is obtained from Eq. (3).

Similarly, when t_{RT} is given, if $\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor$ is larger than D, the average aggregation latency is D/T_{NRT}; otherwise, the average aggregation latency is $1/\lambda_{RT}$. Hence, $E(L|t_{RT})$ is given by

$$E(L|t_{RT}) = \frac{D}{T_{NRT}} \cdot \delta(\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor) + \frac{1}{\lambda_{RT}} \cdot (1 - \delta(\lfloor \frac{t_{RT}}{T_{NRT}} \rfloor))). \tag{7}$$

Then, $E(L)$ is calculated by Eq. (5).

IV. NUMERICAL RESULTS

In our analysis, λ_{NRT} and T_{NRT} are normalized to 1. Figure 3 plots the average aggregation degree as a function of the arrival rate of RT packets. As the RT arrival rate increases, the aggregation degree decreases. This is because the AADA

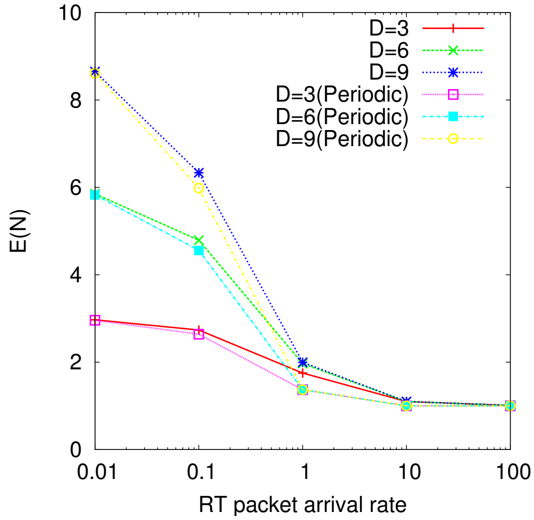


Fig. 3. Average aggregation degree vs. RT arrival rate.

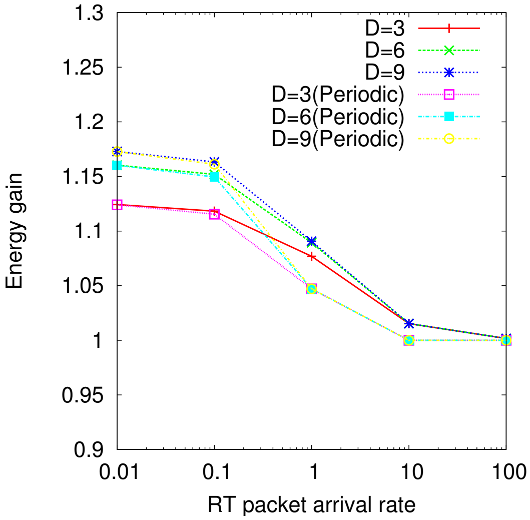


Fig. 4. Energy gain vs. RT arrival rate.

scheme transmits the currently accumulated packets whenever an RT packet arrives. Accordingly, as the RT arrival rate increases, the average aggregation degree converses to 1.0, i.e. no data aggregation. Figure 3 also shows the effect of the aggregation threshold (D). Intuitively, the average aggregation degree is high when the aggregation threshold is set to a high value. As shown in Figure 3, the effect of the aggregation threshold is more notable when the RT packet arrival rate is low. In other words, if the RT packet arrival rate is too high, the effect of the threshold is not remarkable.

When NRT packet arrive periodically, similar trends are observed. As depicted in Figure 3, a higher average aggregation degree is achieved when non periodical arrival of NRT packets is assumed. This implies that if the arrival process of NRT packets is non-periodic (i.e. Poisson distribution), the queue for NRT packets is occupied more aggressively. However, the difference between periodic and non-periodic arrivals is not significant.

From the average aggregation degree, the average energy gain can be defined as follows, when no data fusion [8] is assumed.

$$\frac{E(N)\cdot(E(C)\cdot(H+P))}{E(C)\cdot(H+E(N)\cdot P)}$$

where H and P represent the header and payload sizes of an RT or NRT packet. $E(C)$ denotes the expected number of trials until the transmission succeeds.[3]

Figure 4 shows the energy gain as the RT packet arrival rate increases. Here, the ratio of H to P is set to 1/5. Overall trends are similar to those of Figure 3. Specifically, the energy gain of the AADA scheme becomes more clear as the RT packet arrival rate becomes smaller and/or the aggregation threshold becomes larger. On the other hand, when the RT packet arrival rate becomes larger, the energy gain is not remarkable. This result is consistent with the result of Figure 3. As shown in Figure 3, the average aggregation degree is almost 1 when the RT packet arrival rate is 100. Obviously, the energy gain due to the data aggregation is negligible in this case. Similarly, if the periodical arrival of NRT packets is assumed, the energy gain is low compared with the non-periodical arrival case.

The average aggregation latency is depicted in Figure 5. The aggregation latency increases as the RT packet arrival rate decreases and/or the aggregation threshold increases. In short, there is a trade-off relationship between the aggregation degree and latency. In terms of energy consumption, a higher aggregation degree is preferable. However, the higher aggregation degree results in a longer aggregation latency. In Section II-B, we present an optimization problem based on this relationship. The solution of the problem can be found the result Figure 5. For example, assume that the maximum tolerable aggregation latency (i.e. latency constraint) is 9 and the average RT arrival rate is 0.1. In addition, NRT packets arrive periodically with interval of 1. In this case, the average aggregation latency is 8.46053 and 9.06699 when D is 7 and 8, respectively. Consequently, D should be set to 7, which is the maximum value meeting the given latency constraint.

Let us consider a data aggregation scheme where there is no differentiation between RT and NRT packets and an aggregation packet is transmitted only when the number of accumulated packets (regardless of RT and NRT packets) becomes D. In this scheme, since $E(N)$ is equal to D, more energy saving is achieved compared with the AADA scheme. However, the scheme induces an aggregation latency for RT packet, which is given by $D/(\lambda_{RT}+\lambda_{NRT})$ and prohibits real-time delivery of RT packets in delay sensitive applications.

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[3] In this work, a CSMA-CA style channel contention model is assumed, so that a packet is retransmitted when a collision occurs.

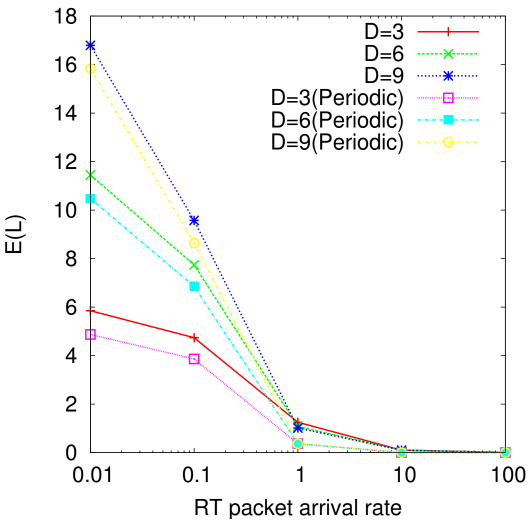

Fig. 5. Average aggregation latency.

V. CONCLUSION

In this paper, a new data aggregation scheme for wireless sensor networks is introduced. The proposed AADA scheme applies different aggregation methods depending on the type of packets (i.e. RT or NRT packets). As a result, the AADA achieves the maximized data aggregation while meeting the constraint for aggregation latency. To evaluate the performance of the AADA scheme, two analytical models for periodical and non-periodical NRT packet arrivals, are developed in terms of the average aggregation degree and latency. Numerical results illustrate the effect of the arrival rate of RT packets and the aggregation threshold. In addition, the energy saving gain is also investigated. Since the AADA scheme is based on a simple queueing scheme, it can be easily implemented in resource constrained sensor nodes. In our future work, we will validate our analytical models via simulations and evaluate the end-to-end delay and energy consumption in an aggregation tree when the AADA scheme is employed.

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