Tradeoff between Delay and Energy Consumption of Partial Data Aggregation in Wireless Sensor Networks

Wuyungerile Li   Daisuke Okamura   Masaki Bandai   Takashi Watanabe
Faculty of Information, Shizuoka University
3-5-1, Johoku, Hamamatsu-Shi, Shizuoka, 432-8011, Japan
{li, okamura, bandai, watanabe}@aurum.cs.inf.shizuoka.ac.jp

ABSTRACT

Recently, wireless sensor networks attract researchers' attention due to its applicability to many fields for effective collection of sensing data within less cost. In wireless sensor networks, due to battery-powered sensor nodes, energy saving is a critical issue. As one of the techniques for energy saving, data aggregation has been proposed. In this paper, we analyze the tradeoff between communication delay and energy consumption of data aggregation. At first, we analyze full aggregation, non-aggregation with Markovian chain. Analytical results show that the non-aggregation method suffers large energy consumption while the full aggregation suffers long transmitting delay. Then, we propose a partial aggregation method called WRP (Waterfalls Random Partial aggregation) which can trade off energy consumption and transmission delay. For the better balance of energy consumption and transmission delay, we utilize several groups of random pushing vectors and investigate them on two criteria based on delay energy products. From the results we find that less arrival data should be aggregated for small data generation rate at nodes to minimize both criteria. For moderate generation rate we must choose a sophisticated random pushing vector depending on the criterion. Furthermore, we extend the analysis in order to discuss the accuracy of sensed data.
Keywords: Wireless Sensor Networks, Data Aggregation, Aggregation Factor, Partial Data Aggregation, WRP.

1 INTRODUCTION

The wireless sensor networks (WSNs) which attract researchers' attention recently consist of large number of inexpensive sensor nodes. These sensor nodes have communication and sensing ability. They sense events and generate event data, then transmit it to the adjacent lower node. By multi-hoping, data will be sent to the sink. In these kinds of networks, the data generated at the nodes are often redundant. Further more, to relay all the receive data to the adjacent lower node is inefficient and consumes much more energy. In WSNs, the sensor nodes are battery-powered, so power – saving is an important issue. In order to save power, various methods are proposed. For example topology control, sleep scheduling, MAC protocols, routing protocols, data aggregation etc. In this paper, we focus on data aggregation for energy saving in wireless sensor networks. Data aggregation [1] is a process that aggregate data from multiple sensors to eliminate redundant data and provide fused information to the base station. From the perspective of energy saving, data aggregation can collect much more significant data. However, transmission delay is equally important to many applications such as disaster monitoring. Therefore to achieve a delay and energy tradeoff networks is necessary. There are several algorithms about data aggregation. PEGASIS [2] is one of the data aggregation protocols. The main idea of PEGASIS is that to form a chain among the sensor nodes through which each node receives from and transmits to close neighbors. Gathered data are sent from node to node, and the nodes take turns to be the leader for transmission to the BS. On the other hand, in LEACH [3] protocol, a small number of clusters are formed in a self-organized manner. A designated node in each cluster collects and combines data from nodes in its cluster and transmits the data to the BS. Directed Diffusion [4] is a kind of data centring routing protocols. Sink broadcasts a message which involves information of interested; the nodes gather and transmit the interested data to the sink. However when the receiving data rate becomes low, the sink starts to attract other higher quality data. Energy-accuracy tradeoffs [5] for periodic data-aggregation is a threshold-based scheme where the sensors compare their fused estimations to a threshold to make a decision regarding transmission. Energy-latency tradeoffs algorithm [6] is for minimizing the overall energy consumption of the networks. The author provided a numerical algorithm for optimal solutions for off-line version of the problem, additionally a pseudo-polynomial time approximation algorithm based on dynamic programming in a priori tree topology was proposed.

For data aggregation, there are two basic methods. They are non-aggregation and full aggregation. The non-aggregation is conducive to transmission delay and the full aggregation is conducive to energy saving. However in some applications, we require both short delay and low energy consumption. For this purpose, we proposed a partial data aggregation method WRP [7], where some data are aggregated and others are not. Data Funneling [8] is another scheme that sends a stream of data from a group of sensor readings to destination. And also proposed a compression method called "coding by ordering" to suppress some readings and encoding the values in the ordering of the remaining packets.

In this paper, at first, we show the analysis process of transmission delay and energy consumption of the non-aggregation as well as the full-aggregation, afterwards show the analysis process of partial data aggregation with Markovian chain. The analytical result shows that when the network is low loaded, the full aggregation is appropriate for power consumption, but it suffers long delay. For suppressing the long transmission delay, WRP (Waterfalls Random Partial aggregation) is proposed as one of partial aggregation methods. Here we discuss tradeoff between transmission delay and power consumption of WRP with several random pushing vectors based on two criteria, EDP (energy-delay product) and CEDP (cubed energy-delay product).

Section 2 describes the sensor network model and defines terminology. Section 3 analyzes the transmission delay and power consumption of the non-aggregation, the full aggregation as well as the partial data aggregation. Section 4 provides evaluation results. Finally, section 5 discusses WRP and the extension of data accuracy.

2 SENSOR NETWORK MODEL

We use a tandem sensor network as shown in Fig. 1. It is the most basic and simplest model that enables us to make an analytic model. The results can be extensible to more complex topology.

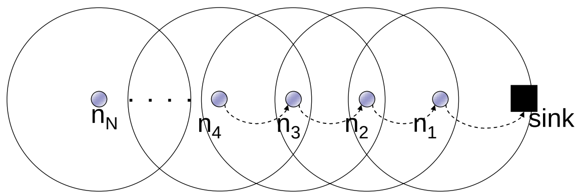

Figure 1: Tandem sensor network

2.1 Definitions

- n_i denotes the *i*-th node from the sink. N is a set of all nodes.
- n_{i+1} is called the adjacent upper node of n_i, while n_{i-1} is the adjacent lower node of n_i. A set of nodes $\{n_k \mid n_k \in \mid N \mid, k > i\}$ denotes the upper nodes of n_i, while $\{n_k \mid n_k \in \mid N \mid, k < i\}$ denotes the lower nodes of n_i.
- E_{ij} denotes the *j*-th event at node n_i.
- D_{ij} denotes the data of event E_{ij}, data size of D_{ij} is identical and fixed.
- Data transmission time $\tau^1(i)$ is defined as a time interval between the instance that a data is transmitted from node n_i and the instance that the data is received by the adjacent lower node n_{i-1}.
- Event E_{ij} may occur at an arbitrary time. Therefore, if E_{ij} occurs during transmitting some data of n_i to n_{i-1}, E_{ij} has to wait to avoid collision. This time is called transmit hold time and denote as $\tau^c(i)$ in this paper.
- Total delay $T(i)$ shows a time interval which starts from data occurs at node n_i, and comes to end as the sink receives D_{ij}.
- In this paper we utilize Omni-directional antenna for communication, so that we need to calculate a time $\tau^n(i)$. It signifies the time interval during which node cannot utilize the medium because of busy channel in Omni-directional transmission.
- Suffixes imi, agg and p attached to terms mean non-aggregation, full aggregation and partial aggregation respectively.
- CSMA is assumed for medium access control.
- The transmission range of each node is assumed d[m].
- If node n_i transmits with data aggregation method, as it receives data from the adjacent upper node n_{i+1}, the arrival data has to wait for a period of time until a new event occurs at node n_i. This time interval called event waiting time in this paper. After sensing data D_{ij}, node n_i aggregates data D_{ij} and all the received data. The data size of the aggregated data can be $A_f (\geq 1)$ times of the generated data size at node n_i. A_f is called aggregation factor here.
- The propagation delay between the adjacent nodes is assumed to be negligible.

2.2 Non-aggregation

Non-aggregation method is one of the timely transmit technologies. Using the non-aggregation method, data is transmitted node by node till the sink. Fig. 2 shows the sequence of the non-aggregation. In Fig. 2, after E_{51} occurs at node n_5, node n_5 sends data D_{51} to the adjacent lower node n_4. During transmitting D_{51}, n_5 exchanges ACK with node n_4. CSMA/CA may defer data transmission. For example, after E_{31} is observed at node n_3, data D_{31} has to wait some time until the channel is idle for avoiding from the collisions on the links.

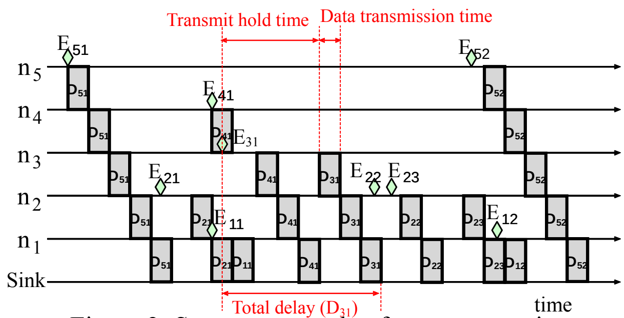

Figure 2: Sequence sample of non-aggregation

2.3 Full aggregation

The main idea of the full aggregation is as follows. When node n_i observes an event, it checks whether there are received data from upper nodes, if so, it aggregates all the data according to aggregation factor A_f and then transmits the aggregated data to the adjacent lower node n_1. If there is no received data from upper node, node n_i transmits the data generated by itself to the adjacent lower node n_{i-1} immediately. If there are arrival data at node n_i from upper nodes, node n_i aggregates all the arrival data and generated data according to the aggregation factor and then transmits it to the adjacent lower node under the first and foremost condition of observing a new event at itself. For example, in Fig.3, at node n_4, D_{51} will not be transmitted until E_{41} occurs. After E_{41} occurs, node n_4 aggregates D_{41} and all the received data into one data and transmits it to node n_3. Note that A_f =1 in this paper.

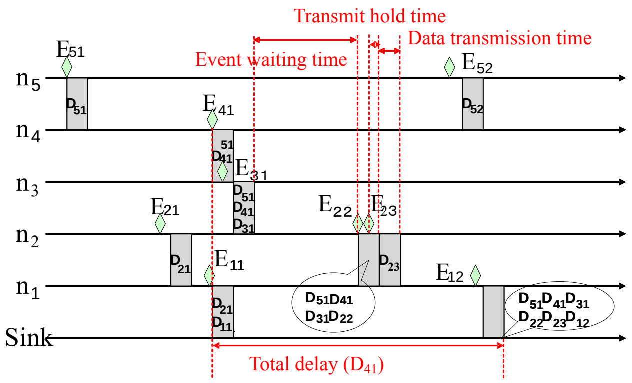

Figure 3: Sequence sample of full aggregation

2.4 Partial data aggregation

In the full aggregation when an event does not occur around node n_i, arrival data from upper nodes suffer long delay to wait for a new event. To overcome this shortcoming, we propose a partial aggregation method. In partial aggregation, some data are aggregated but others are not. As shown in Fig.4, at node n_4, arrival data D_{51} wait for a new event. When a new event E_{41} occurs around node n_4, node n_4 aggregates data D_{51} with the generated data D_{41} and then transmits to the adjacent lower node. At another case, the data D_{32} which arrived at n_2 waits for a new event there. While D_{32} waiting an event, if there is no new event in a specific time, node n_2 aggregates all the arrival data and then transmits it to the adjacent lower node n_1.

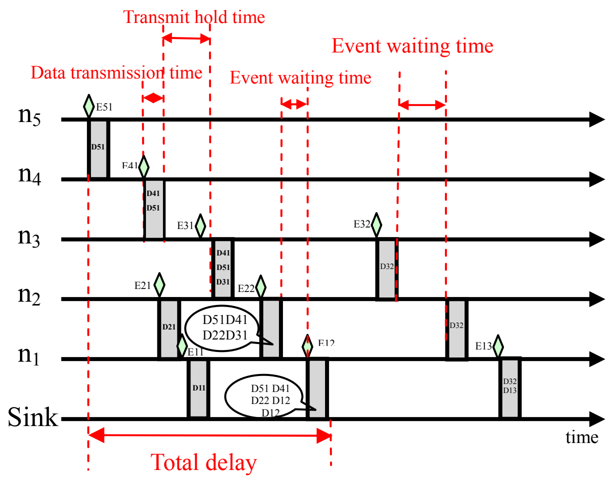

Figure 4: Sequence sample of partial aggregation

3 ANALYSIS

We analyze the queuing model of node n_i with the non-aggregation, the full aggregation and the partial aggregation. Afterward, according to queuing theory and Little's formula, we get the formulations of total delay and energy consumption. [7] provides more detail derivations.

3.1 Non-aggregation

3.1.1 Analytic model

Fig.5 shows the analytic model of node n_i in the non-aggregation.

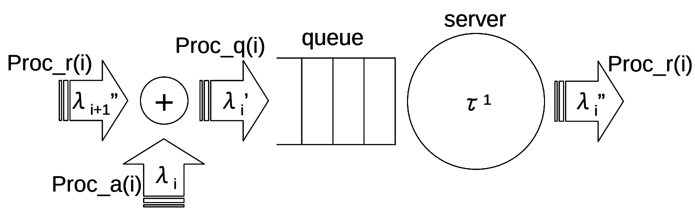

Figure 5: Analytic model of the non-aggregation

3.1.2 Total delay

Total delay $T_{imi}(H)$ is derived as follows where the number of hops from node n_i to the sink is H.

$$T_{imi}(H)=\sum_{i=1}^{H}\left(\tau_{imi}{}^{c}(k)+\tau^{n}(k)\right) \qquad (1)$$

Here $\tau_{imi}^{c}(i)$ is transmit hold time of i-th node. $\tau_{imi}^{n}(i)$ is the time interval that the node n_i can not utilize the channel.

3.1.3 Energy consumption

The H hops networks in the non-aggregation, energy consumption $P_{imi}(i)$ is expressed as follows, where P_t and P_r are energies required for transmitting and receiving a packet, respectively. $N_{imi}(i)$ is the average number of data in the queue.

$$P_{imi}(H)=\sum_{i=1}^{H}\mathrm{N}_{imi}(k)(P_t+P_r) \qquad (2)$$

3.2 Full data aggregation

3.2.1 Analytic model

In the full aggregation, node transmits a data when observes an event data at itself. Fig.6 shows the model of the full aggregation at node n_i. Here queue *A* represents waiting time for an event, whereas queue *B* does back off time for transmission.

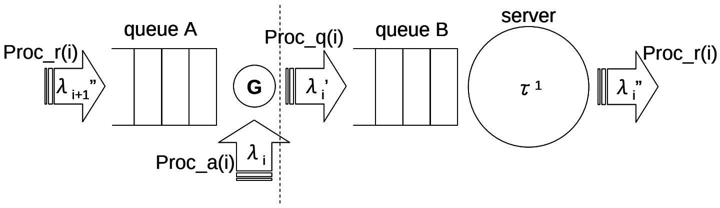

Figure 6: Analytic model at node n_i

3.2.2 Total delay

$T_{agg}(H)$ is derived *H* hops transmission delay of one packet.

$$T_{agg}(H)=\sum_{i=1}^{H}(\tau_{agg}^{e}(i)+\tau_{agg}^{c}(i)+\tau^{n}(i)) \qquad (3)$$

Here $\tau_{agg}{}^{c}(i)$ is transmit hold time of node n_i, $\tau_{agg}{}^{e}(i)$ is event waiting time of node n_i and $\tau^{\mathrm{n}}(i)$ is the time interval that node n_i can not utilize the channel.

3.2.3 Energy consumption

The energy consumption is proportional to the number of data transmissions.

$$P_{imi}(H)=\sum_{i=1}^{H}\mathrm{N}_{imi}(i)(P_t+P_r) \qquad (4)$$

Thus we obtain the total energy consumption where $\mathrm{N}_{agg}(i)$ is the average number of data in the queue *A* and queue *B*.

3.3 Partial aggregation & WRP

3.3.1 Analytic model

Fig.7 shows the model of the partial aggregation at node n_i. Queue *A* represents waiting time for an event, whereas Queue *B* does back off time for transmission.

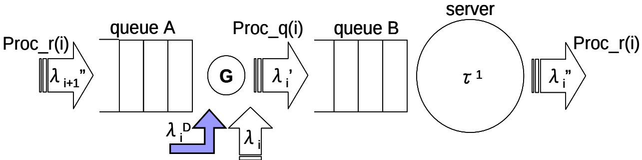

Figure 7: Analytic model of partial aggregation

In Fig 7, Proc_r(i) denotes data arrival process of queue *A*, Proc_q(i) is data arrival process in queue *B*. At transmission process, the differences between the full aggregation and the partial aggregation are arrival process rate λ_i' to the queue *B* and event waiting time. We assume random pushing rate λ_i^D and λ_ι are independent distribution, so that we obtain the relationship as below.

$$\lambda_\iota' = \lambda_i + \frac{\lambda_{\iota+1}''}{\lambda_{\iota+1}''+\lambda_i^D} * \lambda_i^D \qquad (5)$$

3.3.2 Event waiting time

Data waiting in queue *A* for the duration according to the exponential distribution of average $1/(2\lambda_i+\lambda^D)$. So from the state transition rate diagram and Little's formula we obtain event waiting time for partial aggregation.

$$\tau_p^e(i)=\frac{\lambda_{i+1}''}{(2\lambda_i+\lambda_i^D)^2} \qquad (6)$$

3.3.3 Total delay

Total delay of partial aggregation is as follows:

$$T_p(H)=\sum_{i=1}^{H}(\tau_p{}^{e}(i)+\tau_p{}^{c}(i)+\tau^{\mathrm{n}}(i)) \qquad (7)$$

Here $\tau_p{}^{e}(i)$ is average event waiting time of node n_i in partial aggregation. $\tau_p{}^{c}(i)$ is transmit hold time of node n_i. However Equation seems simple, in fact it is very complex function of λ, λ_i and λ_i^D.

3.3.4 Energy consumption

Energy consumption is proportional to the number of data transmissions in wireless sensor networks. So that, we denote $\lambda_i = \lambda$, thus, we can get energy consumption formulation as follow. $\mathrm{N}_p(i)$ is average number of data in the queue.

$$P_p(H)=\sum_{i=1}^{H}\mathrm{N}_p(i)(P_t+P_r) \qquad (8)$$

3.3.5 WRP

WRP (waterfalls random partial aggregation) is one kind of partial aggregation methods where $\lambda_i^D > \lambda_j^D$ for $i > j$. As shown in Fig.8, the purpose of WRP is to increase the rate of transmission, so data is transmitted to the adjacent lower node and avoid from long time delay. Nodes nearer to the sink will transmit larger traffic, which is equivalent to posing the lower nodes larger data generation rate. Thus, in WRP, λ_i^D is set to a smaller value if node n_i is nearer to the sink. In other words, data tends to be rarely aggregated at nodes far from the sink to suppress delay.

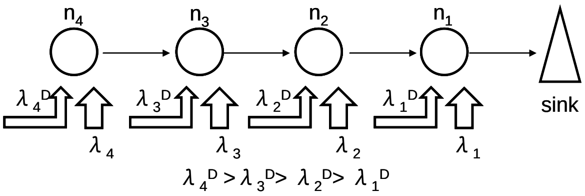

Figure 8: WRP

4 EVALUATION

Here we will show the analytic results of the previous section. The parameters are shown in Table 1.

Table 1 Evaluation parameters

Node distance	10 [m]
Transmission range	11 [m]
Transmission rate	250 [kbps]
Data size	4096 [bit]
Current consumption for transmission	17.4[mA]
Current consumption for reception	19.7[mA]
MAC	CSMA/CA
Routing	DSR

Fig.9 and Fig.10 show the total delay and energy consumption of five hops transmission where $\lambda_i = \lambda$. In Fig.9 the full aggregation has long transmission delay comparing with the non-aggregation as event generation rate is low. As long as total delay is concerned, the non-aggregation should be used at a low event generation rate. The reason why the transmission delay of the full aggregation is concave up is that when event generation rate is low, the received data has to wait longer time at queue *A*. In addition, a node near to the sink, the total delay increases because of the large back off time due to the congestion around the sink. In WRP, λ_i^D are the random pushing rate vectors. We set the vectors randomly [1, 2, 3, 4, 5] here. From the Fig.9 and Fig.10, we find that WRP performances are between those of the non-aggregation and the full aggregation. When λ_i^D is zero, it is fully aggregated and when λ_i^D is infinite, it is fully non-aggregated. Therefore partial aggregation can trade off the total delay and energy consumption by the random pushing rate λ_i^D.

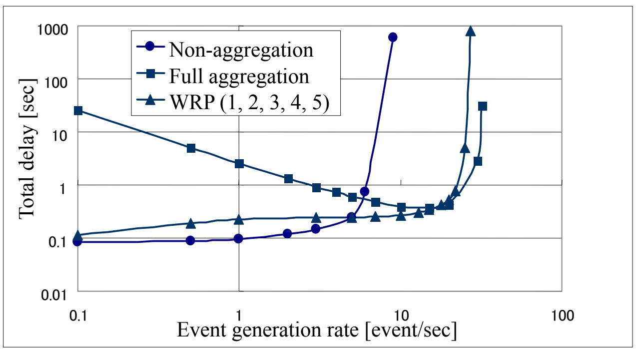

Figure 9: Total delay

Fig.10 shows energy consumption against the whole network when $\lambda_i = \lambda$. In Fig.10, the non-aggregation consumes much more energy than the full aggregation. Therefore, the full aggregation is suitable for less energy consumption while the non-aggregation is efficiency for short delay. But in some applications, we need both short delay and less energy consumption. From Fig.10 we find that WRP can satisfy the requirement of short delay and less energy consumption.

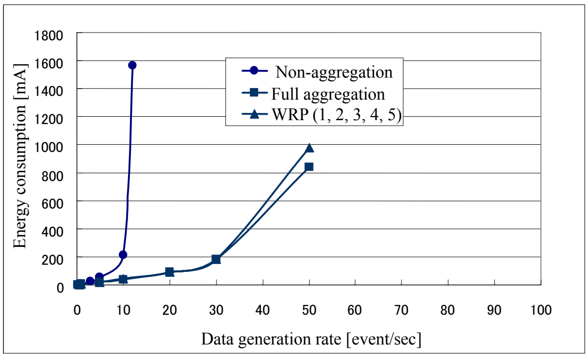

Figure 10: Energy consumption

Fig.11 shows the comparison of network lifetime when $\lambda = 1$. Here we define the networks lifetime is amount to the shortest lifetime of the sensor node in the link. In this figure, node ID is the node order counting from the sink. So here the most energy consumption of node in WRP (node 2) is only about half comparing with the most energy consumption of the node (node 1) in the non-aggregation, it means WRP has about two times network lifetime compare to the non-aggregation.

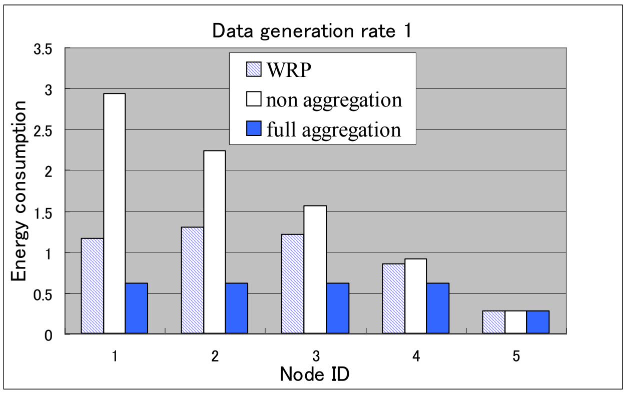

Figure 11: Energy consumption of nodes

5 DISCUSSION

5.1 Delay Energy Tradeoff

In this section we investigate the tradeoff on two criteria, EDP (Energy Delay Product) and CEDP (Cubed-Energy Delay Product). That is that EDP = energy*delay and that CEDP = energy*energy*energy*delay. CEDP is a criterion where we consider that energy is more important than delay. To minimize EDP and CEDP, we may calculate the optimal vector. However, equation (7) and equation (8) are too complex. Instead, here, we discuss those criteria with the some specific random pushing rate vectors. In the figures, the random pushing rate vectors are as follow. T1=[0.2, 0.4, 0.6, 0.8, 1], T2=[1, 2, 3, 4, 5], T3=[3, 4, 5, 6, 7], T4=[6, 7, 8, 9, 10].

5.1.1 Data generation rate λ=1

Fig.12 and Fig.13 show the EDP and CEDP criteria when λ=1. The line denotes potential value of the product of transmission delay and energy consumption. E.g. the line EDP1.2 shows that the product is 1.2 anywhere on the line.

From Fig.12 when data generation rate λ is small (λ≤1), T4 is the least product in criteria EDP. In Fig.13 when the data generation rate is small, due to the importance of energy consumption, we find that T1 is the best product.

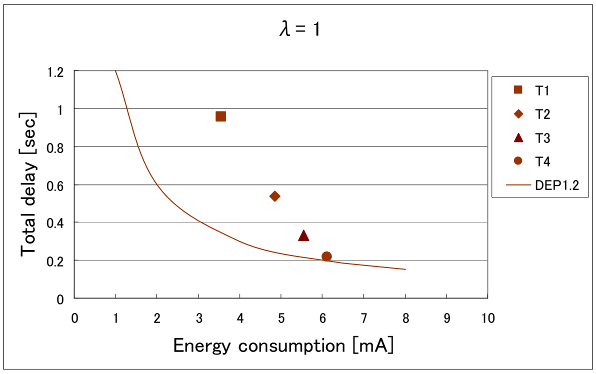

Figure12: EDP (λ=1)

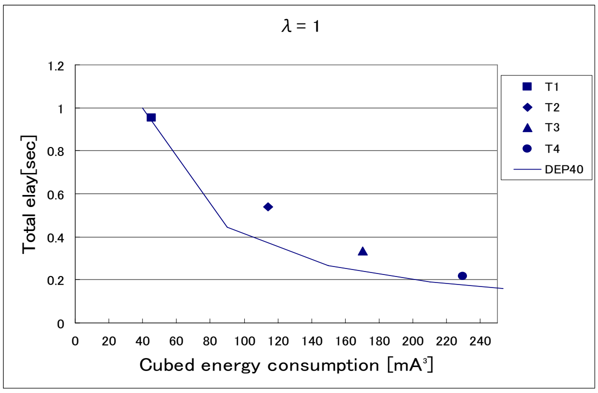

Figure13: CEDP (λ=1)

5.1.2 Data generation rate λ=3

In Fig.14 when λ is bigger (λ=3), the result shows T_4 is the least product in EDP, while T_1 is the least product in CEDP. The reason is considered as follows.

As λ=3, the arrival data rate is much more than generated data rate at a node. Therefore the event generation rate at the node does not satisfy the transmitting requirement. Thus, there will be congestion caused by overmuch arrival data; thereby it needs bigger random pushing rate at this node. In the case of allowed energy consumption, we select T_4 to get shorter transmission delay or select T_1 to get less energy consumption. In Fig.15, since energy consumption is more significant than transmission delay, hence T_1 is the best random pushing vector.

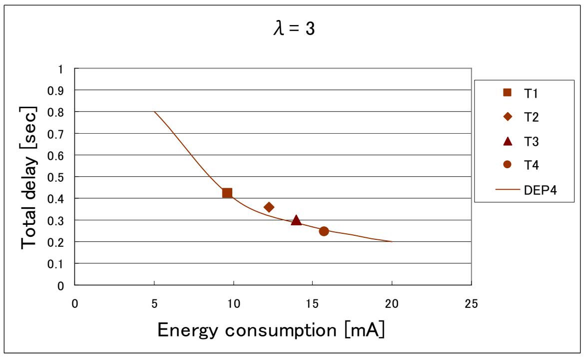

Figure14: EDP (λ=3)

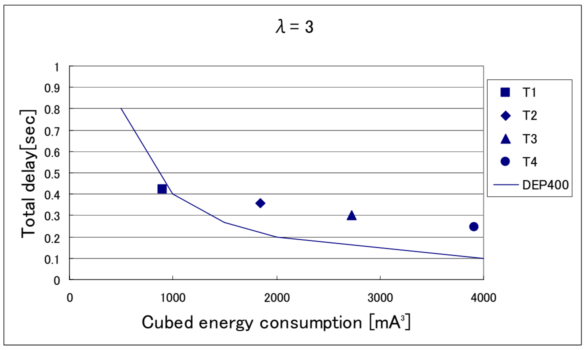

Figure15: CEDP (λ=3)

5.1.3 Data generation rate λ=4.

In Fig.16 and Fig.17 where data generation rate λ=4, we find that T1 is the best in both EDP and CEDP. Since the data generation rate can offer enough transmission to the arrival data. Therefore big random pushing rate is unnecessary here.

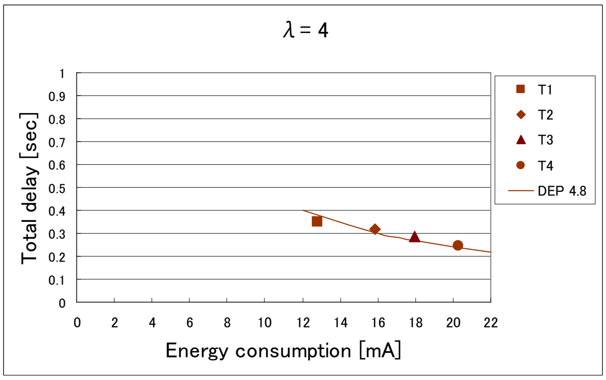

Figure16: EDP (λ=4)

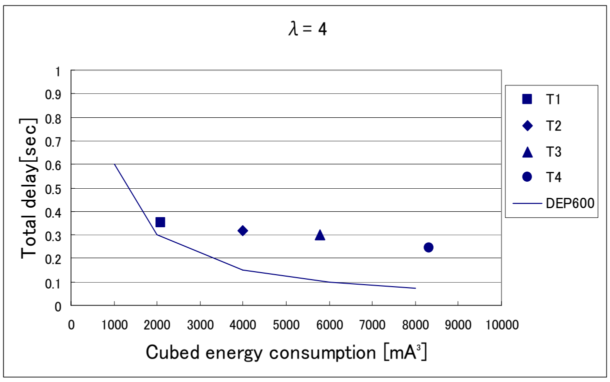

Figure17: CEDP(λ=4)

5.2 Data Accuracy

So far we have discussed partial data aggregation-WRP for trading off the delay and energy consumption. Here we discuss about data accuracy. In many applications, we need more accurate data to monitor and control the objects. In large field nature monitoring networks, we assume a node n_3 needs three hops to reach to the sink. If an event at node n_3 is temperature 900°c, at node n_2 is 600°c, at node n_1 is 300°c, according the aggregation factor of the full aggregation, the sink gets the aggregated data of 600°c. If the threshold of combustion is 800°c at node n_3, then there occurs fire accident, but sink does not know about it in time. In another application, at water power plant, we need the most accurate data of the water coming from the upper reaches in every time interval, so that we can control the height of water to work in a best status. In this way, we can utilize least water to get most electric energy. This is the purpose of green computing.

5.2.1 Accuracy and aggregation factor

Here we discuss the aggregation factor A_f and data accuracy. Aggregation factor denotes the proportion of aggregated data size and generated data size. That is the data size of aggregated data is A_f times of generated data size. In the previous sections we assume A_f=1. A_f=1 means that aggregated data size is equals to generated data size at a node, and there is only one generated data at one time. From a view point of accuracy, if A_f=1, the data will deviate too much from its original value.

One of the definitions of data accuracy is

$$Ac = \frac{\text{number of collected data at sink}}{\text{number of sensed data}}$$

According to this equation, we know that the aggregation factor A_f can reflect data accuracy. For example, let's consider data accuracy of the full aggregation in five hops transmission. As A_f=1, the number of whole sensed data at all nodes is 100 and the number of collected data at sink is 20*1=20. In this case, Ac=0.2. At other case, while A_f =1.5, there will be 20*1.5=30 data collected at the sink. Thus, Ac=0.3.

5.2.2 Analysis

We analyze while aggregation factor $A_f \neq 1$ in the condition of the full aggregation. The arrival data to queue B have two kinds of data size, one is A_f time of generated data and they other is the same size with generated data. Since arrival data from the adjacent upper node has to wait a generated data and then be transmitted, hence the arrival data rate to queue B is the same with data generation rate and approximated to Poisson distribution. Here we assume that the data rate which aggregates with arrival data is abide by exponential distribution of $1/2\lambda_i$. Therefore we get the average data size in queue B as below:

$$S_{av} = \frac{S_i * (A_f + 1)}{2} \qquad (9)$$

Here S_i is generated data size and S_{av} is average data size after aggregated. Same with the full aggregation we had analyzed in previous section, the service process becomes data transmission time $\tau^1(i)$. $\tau^1(i)$ is derived data transmission rate Vc and average data size S_{av}. So the average data transmission time $\tau^1{}_{agg}(i)$ is

$$\tau^1(i) = \frac{S_{av}}{v_c} \qquad (10)$$

$$\tau^1{}_{agg}(i) = \frac{1}{(1-\alpha_i)}\frac{S_{av}}{v_c} \qquad (11)$$

Here α_i denotes the utilization of server, $\alpha_i = \lambda_i \tau^1(i)$.

According the queuing theory, we get the total delay and total energy consumption.

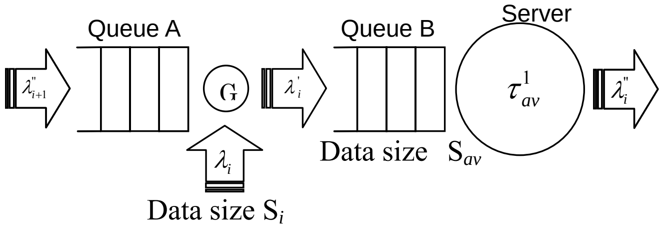

Figure.18 Extension of aggregation factor, A_f

5.2.3 Evaluation

We analyze total delay, total energy consumption under the criteria of EDP and CEDP as the data aggregation factor A_f = 1.5 with the same parameters of Section 4. The figures are as follow:

From Fig.19 we find that total delay in the full aggregation and WRP has almost identical values as Af=1 and Af=1.5 while data generation rate is small. Moreover data generation rate is bigger, energy consumption is bigger as A_f = 1.5. Here WRP random pushing rate vectors T= [1, 2, 3, 4, 5].

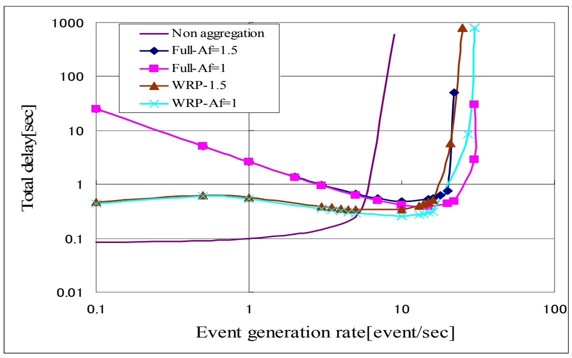

Figure 19: Total delay

From Fig.20 when data generation rate is very small, the energy consumption is similar in all the conditions. Meanwhile data generation rate is big, WRP and full aggregation have similar power consumption as A_f =1.5 and A_f =1. However when data generation rate is bigger, in the case of A_f =1.5 consumes more energy than A_f =1.

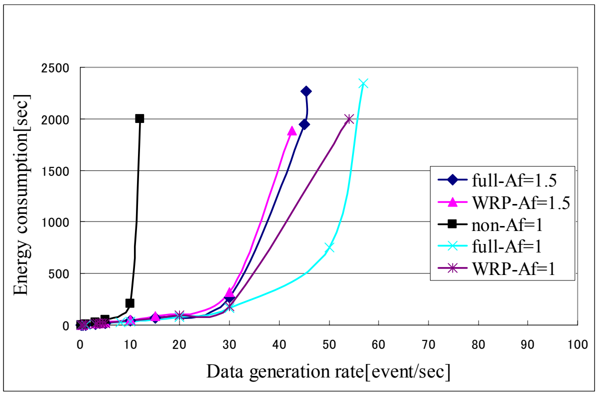

Figure 20: Total energy consumption

Here we discuss total delay when data generation rate λ=3 under the criteria of EDP and CEDP.

From Fig.21 we find that the three point A_f =1(T1), A_f =1(T3), A_f =1(T4) all are the similar values (declare that T1, T2, T3, T4 are the same parameters as previous section). However there are three different conditions. When we minimum energy consumption, we can select T1, while we minimum transmission delay, we select T4. Nevertheless if we want to get a tradeoff condition, we could select T3. We find from the Fig.21 that when we need more accurate data, we sacrifice about 1.2 times of energy to select A_f= 1.5.

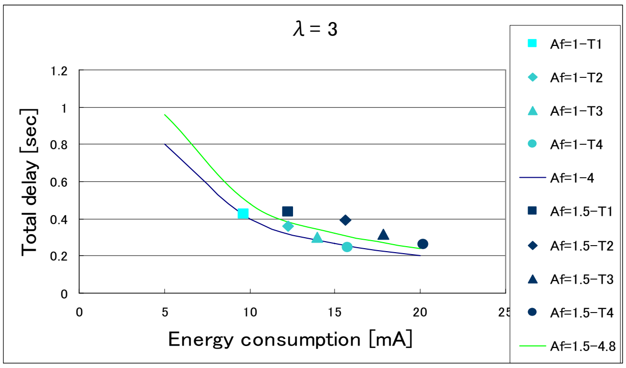

Figure 21: A_f=1-EDP

Fig.22 shows delay energy product under the criteria of CEDP as data generation rate λ=3. From the eight points we find the best one is A_f=1(T1). A_f=1(T2) and A_f =1.5(T1) have the similar CEDP value. So without consideration of total delay, we select A_f=1(T2) and get about 1.5 times accurate data.

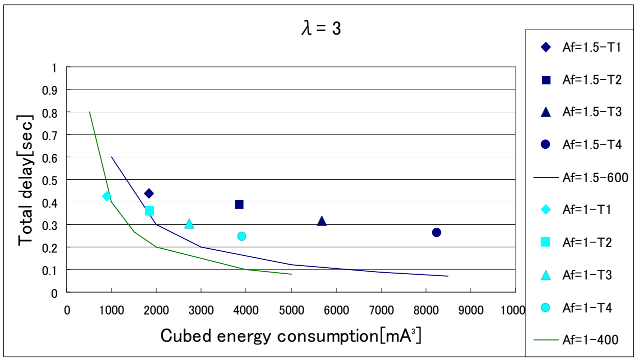

Figure 22: A_f =1.5-CEDP

6 CONCLUSIONS

This paper discussed the tradeoff between energy consumption and transmission delay in data aggregation techniques with Markovian chain. The results show that WRP can trade off transmission delay and energy consumption as long as extends network lifetime. Then we discuss the product between energy and delay with two criteria, EDP (Energy Delay Product) and CEDP (Cubed-Energy Delay Product). The results show the least product at different data generation rate. Although the network model is simple, the result can be applicable to more complex structure. At last we discuss about the relationship between data accuracy and aggregation factor in WRP. From the results we find that delay, energy and accuracy affecting each other; we can select the best WRP random pushing vectors according our requirements. The future works include analysis of WRP to more complex networks and extension of aggregation factor.

ACKNOWLEDGMENTS

This work is supported by a Grant-in-Aid for Scientific Research (A) (no. 17200003 and 20240005).

REFERENCES

[1] R. Rajagopalan, P. Varshney, “Data-Aggregation Techniques in Sensor Networks: A Survey,” IEEE Comm. Surveys and Tutorials, pp. 48-63, 2006.

[2] S. Lindsey, C. Raghavendra, and K. M. Sivalingam, “Data Gathering Algorithms in Sensor Networks Using Energy metrics,” IEEE Trans. Parallel and Distributed Systems, vol. 13, no. 9, pp. 924–35, 2002.

[3] C. Intanagonwiwat, R. Govindan, D. Estrin, “Directed Diffusion: A Scalable and Robust Communication Paradigm for sensor networks,” Proc. ACM Mobicom'00, pp. 55-67, 2000.

[4] W. R Heinzelman, “Application-Specific Protocol Architectures for Wireless Networks,” Ph.D. thesis, Massachusetts Institute of Technology, 2000.

[5] A. Boulis, S. Ganeriwal and M. B. Srivastava, “Aggregation in sensor networks: an energy–accuracy trade-off” 1st IEEE Int’l. WKsp. Sensor Network Protocols and Applications, USA, May 2003.

[6] Y. Yu, B. Krishnamachari and V. K. Prasanna, “Energy-Latency Tradeoffs for Data Gathering in Wireless Sensor Networks” IEEE INFOCOM, Mar. 2004.

[7] D. Okamura, W. Li, M. Bandai, T. Watanabe: “Fundamental Analysis towards Partial Data Aggregation in Wireless Sensor Networks”, WPMC’2009, Sep.2009.

[8] D. Petrović, R.C. Shah, K. Ramchandran, J. Rabaey, “Data Funneling: Routing with Aggregation and Compression for Wireless Sensor Networks” sensor network protocols and applications, 2003, IEEE international workshop.