Autonomous data gathering mechanism with transmission reduction for wireless sensor networks

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***Abstract*—In this paper, we propose an autonomous and energy-efficient data gathering mechanism with transmission reduction for wireless sensor networks (WSNs). In our proposed mechanism, sensor nodes schedule their message transmission timing in a self-organizing manner such that they can gather sensor data over a whole WSN and transmit that data to a sink node while switching between a sleep state and an active state. In addition, each sensor node determines the redundancy of its sensor data according to overheard messages so that only necessary sensor data are gathered and transmitted to the sink node. Our proposed mechanism does not require additional control messages and enables both data traffic and control traffic to be drastically reduced. Through simulation experiments, we confirmed that the number of message transmissions can be reduced by up to 77% with our proposed mechanism compared to a conventional mechanism.**

***Index Terms*—wireless sensor networks, data gathering, data aggregation, spatial interpolation, traveling wave**

I. Introduction

Wireless sensor networks (WSNs) have attracted much attention in recent years. In particular, monitoring applications such as surveillance or environmental monitoring are among the most promising applications of WSNs. In a monitoring application, it is assumed that a large number of battery-powered sensor nodes are randomly deployed over a large target region. The application requires a WSN to periodically provide information on the whole target region, for example, distribution of temperature. Due to several restrictions such as limited battery capacity, random deployment, and a large number of unstable sensor nodes, WSN control mechanisms should be energy-efficient, adaptive, robust, fully-distributed, and self-organizing.

Many studies have been conducted on energy-efficient techniques for WSNs. One of the key techniques is *sleep scheduling* [1]. To enable WSN sleep scheduling in a self-organizing manner, we have proposed a traveling wave-based communication mechanism (WAVE) [2]. WAVE can organize a variety of periodic communications with sleep scheduling depending on dynamically changing application requirements. In the case of periodical data gathering from every sensor node for transmission to a sink node, WAVE message transmissions begin from the edge of the WSN and end at the sink node. When sensor nodes at the farthest hop distance from the sink node transmit messages, the sensor nodes that are closer to the sink node by one hop (i.e., the next-hop nodes) are scheduled to wake up to receive the messages. After a certain period, they also transmit messages under a timing such that their next hop sensor nodes awaken to receive the messages. At this same time, the farthest sensor nodes also receive the messages and go to sleep. As a consequence of such scheduling, a concentric circle-shaped message propagation from the edge of the WSN to the sink node is accomplished. In WAVE, each sensor node periodically broadcasts a message, including its sensor data and a small amount of control information, in accordance with its own timer. The sensor node timer is adjusted appropriately according to the reception of messages from neighbor sensor nodes. WAVE does not require additional signaling.

As for monitoring applications, *data aggregation* is also an important energy-efficient technique [3]. Data aggregation techniques reduce the amount of data to be transmitted by using the feature that sensor data generally have spatial correlations. Many data aggregation mechanisms have been proposed [3–5]; however, these proposals require message exchanges in order to share information. We have proposed an overhearing-based data aggregation mechanism that, unlike previous proposals, utilizes spatial interpolation (ODAS) [6]. In ODAS, each sensor node overhears messages and determines the redundancy of its sensor data by using sensor data overheard from neighbor nodes. A sensor node does not transmit its sensor data when it determines its sensor data to be redundant. Therefore, only the necessary sensor data are gathered and transmitted to the sink node. Since ODAS does not require control messages, both data traffic and control traffic can be drastically reduced. However, ODAS requires some assumptions on the under layer, such as ideal time division multiple access (TDMA) scheduling, time synchronization among sensor nodes, and ideal routing between sensor nodes and the sink node.

In this paper, we propose an autonomous and energy-efficient data gathering mechanism. We integrate our communication mechanism and data aggregation mechanism (i.e., WAVE and ODAS) in order to further reduce energy consumption in monitoring applications. As in both these previous projects, the mechanism proposed in the present work does not require signaling and control messages. Through simulation experiments, we evaluate our proposed mechanism against conventional mechanisms in terms of number of non-redundant sensor data, number of message transmissions, and data gathering delay.

The remainder of this paper is organized as follows. In Section II, we first describe the assumptions upon which we

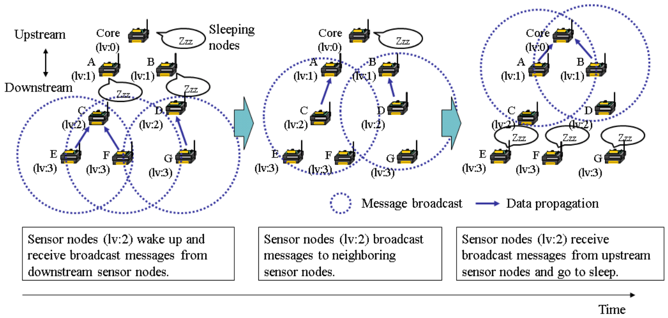


Fig. 1. Basic behavior of WAVE in the case of data gathering.

rely in this paper. Next, we briefly describe the conventional mechanisms in Section III. Then, in Section IV, we propose an autonomous data gathering mechanism with transmission reduction. We evaluate our proposed mechanism in Section V. Finally, in Section VI, we conclude this paper.

II. Assumptions and definitions

In this paper, we assume a multi-hop WSN, comprised of a single sink node and a set of sensor nodes $\mathcal{N} = \{n_1, \cdots, n_N\}$ deployed in a flat region. All sensor nodes have the same circular radio transmission range (radius of R). Each sensor node knows its own location and the locations of its neighbor sensor nodes through the use of a global positioning system (GPS) or some localization mechanism [7]. Here, the neighbor sensor nodes of a sensor node are defined as the set of sensor nodes that exist within range R from the sensor node. The sink node knows the location of all sensor nodes.

The monitoring application requires the WSN to periodically provide information on the entire target region, for example, distribution of temperature. The cycle duration T and acceptable error range E are set in advance. At interval T, each sensor node senses some physical phenomena (e.g., temperature) and sends the sensor data to the sink node. The acceptable error range is the acceptable difference between the actual sensor data value and an estimated sensor data value for all sensor nodes. The estimated sensor data value is a sensor data value estimated at the sink node based on a data aggregation mechanism. Thus, the following condition should be satisfied for all sensor nodes:

$$|d_i - \hat{d}_i| \leq E \quad (\forall n_i \in \mathcal{N}), \tag{1}$$

where d_i and $\hat{d}_i$ stand for the actual sensor data value and the estimated sensor data value of sensor node n_i, respectively.

III. Conventional mechanisms

A. WAVE [2]

We first briefly introduce our traveling wave-based communication mechanism. As the medium access control (MAC) protocol, WAVE assumes a carrier sense multiple access (CSMA)-based protocol, which is widely implemented in commercial sensor units such as MICAz [8]. WAVE can organize two types of message propagation, *data diffusion* and *data gathering*, depending on dynamically changing application requirements. In WAVE, any sensor node can become a point, called a *core node*, from which messages are disseminated or to which messages are gathered. When there is no session, sensor nodes transmit messages at their own timing independently from the others. If there is a session, concentric circle-shaped message propagation, that is, a *traveling wave*, is generated in a self-organizing manner under which the direction of the traveling wave is from the core node to the edge of the WSN in data diffusion or opposite in data gathering. Figure 1 shows an overview of WAVE in the case of data gathering from all sensor nodes to the core node from the viewpoint of sensor nodes two hops away from the core node. To autonomously generate and maintain concentric circle-shaped traveling waves, WAVE adopts a pulse-coupled oscillator model which explains a biological synchronization apparent in groups of flashing fireflies [9].

In the following, we explain the behavior of WAVE from the viewpoint of data gathering. In WAVE, each sensor node maintains a phased timer, a phase response curve (PRC) function, a level value, and some control parameters. The phase shifts toward T as time passes. When it reaches T, it expires and goes back to zero. The PRC function determines the amount of phase shift on receiving a message. By configuration the PRC function appropriately, the desired traveling wave appears regardless of the initial phase condition of oscillators [2]. The level value indicates the number of hops from a core node, and it is initialized when a new session starts.

A sensor node periodically broadcasts messages containing its control information and sensor data whenever its phase expires. When a sensor node receives a message from a neighbor sensor node whose level value is smaller, it sets its level value as the received value plus one. Then, it is stimulated to generate and maintain a traveling wave. Stimulated sensor node shifts its phase based on the PRC function. To avoid being stimulated by delayed messages, a sensor node is not stimulated by messages from other sensor nodes with a smaller level value for a certain duration after it has already been stimulated. When a sensor node receives a message whose level value is larger, the sensor node deposits the received sensor data in its local buffer.

Through such mutual interactions among neighbor sensor nodes, concentric circle-shaped traveling waves are autonomously generated. Then, a sensor node starts sleep scheduling by turning off its modules between successive receptions and transmissions. We note here that each sensor node only broadcasts messages in accordance with its own timer. WAVE does not require additional signaling or control messages to generate and maintain traveling waves. However, WAVE does not consider data aggregation. If the application accepts a certain range of error among sensor data value, the amount of traffic can be more reduced. In addition, since WAVE is a broadcast-based communication mechanism, sensor data are forwarded to the sink node in multi-paths, which generally consumes more energy in comparison with single-path forwarding.

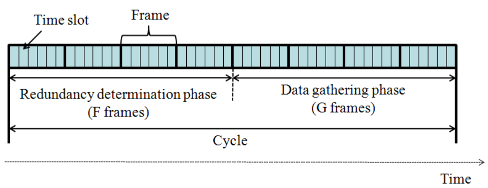
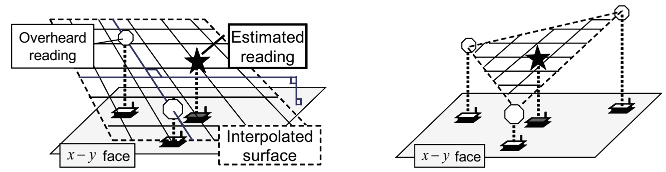


Fig. 2. Frame structure of ODAS in one cycle.



(a) Using two sensor data. (b) Using three sensor data.

Fig. 3. Spatial interpolations in ODAS.

B. ODAS [6]

1) Assumptions of ODAS: We next briefly introduce our data aggregation mechanism. In ODAS, TDMA is assumed as the MAC protocol. In TDMA, time is divided into time slots. Each sensor node is assigned a time slot and is allowed to transmit a message including a sensor data to a neighbor sensor node within its assigned time slot. In addition, multiple time slots are grouped into a frame, with each time slot appearing within the period of the frame. In ODAS, it is assumed that an optimum time slot assignment is achieved in advance by considering radio interference relationships. It is also assumed that all sensor nodes know the time slots assigned to themselves and to their neighbor sensor nodes. Therefore, each sensor node can implement sleep scheduling by turning off its modules during unrelated time slots. In addition, clock is assumed to be synchronized among all sensor nodes by applying some conventional protocol [10].

2) Overview of ODAS: In ODAS, each cycle consists of two phases, namely, the *redundancy determination phase* and the *data gathering phase*, as shown in Fig. 2.

The redundancy determination phase consists of F frames. In the beginning frame, some sensor nodes first transmit messages without overhearing. Here, a message consists of sensor node identifier and the sensor data of the node. These sensor nodes are evenly distributed within the target region. When a sensor node overhears a message from a neighbor sensor node, it determines the redundancy of its sensor data as described in Section III-B3. If a sensor node determines that its sensor data is not redundant, it transmits a message in a succeeding frame. Such message receptions and transmissions are repeated during the redundancy determination phase.

The data gathering phase consists of G frames. The number of frames G should be configured based on the maximum hop distance between the sink node and sensor nodes. During the data gathering phase, sensor nodes that have non-redundant sensor data transfer their sensor data to the sink node through a tree-shaped communication route that is constructed in advance of this phase. On the other hand, sensor nodes that have redundant sensor data do not transfer their sensor data. Such missing sensor data, however, can be restored at the sink node by satisfying Eq. (1) because the sink node can reenact the interpolation process performed by each sensor node.

3) Redundancy determination using overhearing sensor data: To determine the redundancy, ODAS uses three-dimensional spatial interpolation. Here, we assume an $x-y-z$ space in which the $x-y$ face corresponds to the target flat space for sensing; in other words, the x and y coordinates represent the sensor node's location, and the z coordinate corresponds to the sensor data value at the location. First, a sensor node calculates the estimated sensor data value by the following procedure:

- When the sensor node stores only one overheard sensor data, the sensor node only regards this sensor data value as its estimated sensor data value.
- When the sensor node stores two overheard sensor data, as shown in Fig. 3(a), the sensor node first derives a flat surface including the line containing the overheard sensor data value and its perpendicular, which is parallel to the $x-y$ face. Next, the sensor node chooses the value, whose x and y coordinates correspond to the ones of itself, from the derived surface as its estimated sensor data value.
- When the sensor node stores more than two overheard sensor data, as shown in Fig. 3(b), the sensor node first chooses three nodes whose locations construct a triangle containing the location of the sensor node. If there are multiple candidates, the sensor node chooses ones in which the total distance between the three sensor nodes and itself is the smallest. On the other hand, if there is no set of sensor nodes that construct a triangle containing the sensor node, the sensor node chooses three sensor nodes in which the total distance between the three sensor nodes and itself is the smallest. Next, the sensor node derives a flat surface that contains the triangle constructed of the overheard sensor data value of the chosen three sensor nodes. Finally, it chooses a value whose x and y coordinates correspond its own coordinates, from the derived surface as its estimated sensor data value.

After calculating the estimated sensor data value, each sensor node determines the redundancy of its sensor data value. In this procedure, the node evaluates the following condition:

$$|d_i - \hat{d}_i| \leq E. \tag{2}$$

When this condition is false, the sensor node determines that its sensor data is not redundant. Otherwise, it determines that its sensor data is redundant.

4) Feature of ODAS: By the redundancy determination mechanism of sensor nodes, ODAS can drastically reduce the amount of message transmissions. However, ODAS put some assumptions for the under layer as described in Section III-B1. Although ODAS itself does not need control messages, TDMA scheduling, time synchronization, and routing

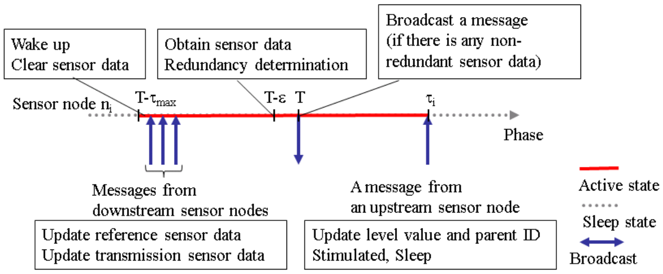


Fig. 4. Sensor node behavior in our proposed mechanism.

generally require overhead or control messages. To accomplish autonomous and energy-efficient scheduling, we apply WAVE for the under layer of ODAS in the following section.

IV. Autonomous data gathering mechanism with transmission reduction

In this section, we propose a data gathering mechanism for WSNs and which integrates WAVE and ODAS. The basic behavior of our proposed mechanism is based on WAVE by regarding the core node as the sink node.

A. Control parameters

In our proposed mechanism, sensor node $n_i \in \mathcal{N}$ has a timer with phase $\phi_i \in [0, T]$ $(d\phi_i/dt = 1)$. It maintains level value l_i, offset τ_i $(\tau_{min} \leq \tau_i \leq \tau_{max})$, PRC function $\Delta_i(\phi_i)$, parent node identifier n_i^p, a set of reference sensor data $\mathcal{D}_i^r$, and a set of transmission sensor data $\mathcal{D}_i^t$. The level value indicates the number of hops from the sink node and is initialized to a sufficiently large value. The offset defines the interval of message transmission between a sensor node of level $l-1$ and that of level l. Offset τ_i is chosen randomly to avoid synchronous message transmission among sensor nodes of the same level. The maximum offset τ_{max} is determined taking into account the density of sensor nodes over the whole WSN. To autonomously generate concentric circle-shaped traveling waves for message propagation regardless of the initial phase condition, we use the following PRC function for all sensor nodes [2].

$$\Delta_i(\phi_i) = a \sin \frac{\pi}{\tau_i} \phi_i + b(\tau_i - \phi_i), \tag{3}$$

where a and b are parameters which determine the speed of convergence. The parent node identifier is used to reduce the amount of message transmissions due to the multi-path effect that arises as a consequence of broadcast-based communication. The set of reference sensor data $\mathcal{D}_i^r$ is only used to determine the redundancy of sensor data. The set of transmission sensor data $\mathcal{D}_i^t$ is used both to determine the redundancy of sensor data and to transfer it to the upstream sensor nodes.

B. Behavior of sensor node

Sensor node n_i behaves in accordance with its phase ϕ_i, as shown in Fig. 4. In the following, we describe the behavior of a sensor node after the traveling wave is generated and the sleep scheduling of sensor nodes is already started.

When phase ϕ_i becomes $T - \tau_{max}$, sensor node n_i wakes up. After waking up, sensor node n_i clears the set of reference sensor data $\mathcal{D}_i^r$ and the set of transmission sensor data $\mathcal{D}_i^t$. Then, it waits for message reception. Downstream sensor nodes are scheduled to broadcast messages when phase ϕ_i is between $T - \tau_{max}$ and T from the viewpoint of sensor node n_i. A broadcast message from neighbor sensor node n_j contains the set of transmission sensor data $\mathcal{D}_j^t$, level value l_j, its identifier n_j, and parent node identifier n_j^p.

When sensor node n_i receives a message from downstream sensor node n_j with $l_j = l_i + 1$ and $n_j^p \neq n_i$, sensor node n_i adds the received sensor data $\mathcal{D}_j^t$ to its set of reference sensor data $\mathcal{D}_i^r$. On the other hand, when sensor node n_i receives a message from downstream node n_j with $l_j = l_i + 1$ and $n_j^p = n_i$, sensor node n_i adds the received sensor data $\mathcal{D}_j^t$ to its set of transmission sensor data $\mathcal{D}_i^t$.

When phase ϕ_i reaches $T - \epsilon$, sensor node n_i reads sensor data value d_i from its sensor device. The parameter ϵ $(0 < \epsilon < \tau_{min})$ corresponds to the sensing delay. Then, sensor node n_i determines the redundancy of its sensor data using the set of sensor data which satisfies $\mathcal{D}_i^{det} = \{d_k \in \mathcal{D}_i^r \cup \mathcal{D}_i^t \mid l_k = l_i + 1\}$. The redundancy determination process is same as that in ODAS (see Section III-B3). If sensor node n_i determines that its sensor data is not redundant, it adds its sensor data to its set of transmission sensor data $\mathcal{D}_i^t$.

When phase ϕ_i reaches T, sensor node n_i checks the set of transmission sensor data $\mathcal{D}_i^t$. If there is any sensor data in $\mathcal{D}_i^t$, sensor node n_i broadcasts a message, which is received by any awake sensor node in the range of radio communication. On the other hand, if there is no sensor data (i.e., $\mathcal{D}_i^t = \emptyset$), sensor node n_i does not broadcast a message. The phase ϕ_i, reaching T, goes back to zero.

After the phase returns to zero, sensor node n_i stays awake and waits for message reception from an upstream sensor node. When sensor node n_i receives a message from sensor node n_j with $l_j < l_i$, it sets its level value $l_i = l_j + 1$ and parent identifier $n_i^p = n_j$. It then shifts its phase by an amount $\Delta_i(\phi_i)$ in Eq. (3) so as to maintain a traveling wave. After that, sensor node n_i goes to sleep. In a steady-state situation, sensor node n_i receives the message from the upstream sensor node when its phase ϕ_i reaches τ_i. Therefore, sensor node n_i stays awake for the duration of $\tau_{max} + \tau_i$ in one data gathering cycle T; in other words, the duty cycle becomes $(\tau_{max} + \tau_i)/T \simeq 2\tau_{max}/T$.

C. Discussion on the redundancy determination

In our proposed mechanism, the redundancy of each sensor datum is determined at the same time as data gathering, whereas ODAS assumes two phases (i.e., the redundancy determination phase and the data gathering phase). Since each sensor node is scheduled to broadcast a message before its upstream sensor nodes broadcast messages (see Fig. 4), the sensor data from upstream nodes cannot be used for

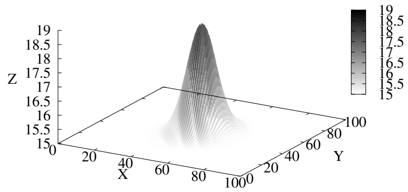


Fig. 5. Two-dimensional normal distribution of temperature.

redundancy determination. In addition, the traveling wave-based mechanism does not ensure the order of message transmission among sensor nodes of the same level value. Since the sink node should reenact the interpolation process performed by each sensor node to restore any missing sensor data, sensor data from same-hop nodes cannot also be used for redundancy determination. For these reasons, in our proposed mechanism, each sensor node only uses sensor data from downstream nodes to determine the redundancy of its sensor data. Therefore, a sensor node cannot choose three sensor nodes whose locations construct a triangle containing the location of the sensor node as described in Section III-B3. As a result, the performance of redundancy determination differs between our proposed mechanism and the ODAS mechanism.

V. Simulation experiments

A. Simulation settings

In the simulation experiments, we consider a WSN of $N = 200$ sensor nodes randomly distributed in a 100 m $\times$ 100 m region. A sink node is located at a corner of the region. The radio communication range R is fixed at 20 m. We use temperature data of a two-dimensional normal distribution as shown in Fig. 5. The monitoring application requires that the temperature distribution over the whole WSN be gathered at an interval of $T = 60$ s with an acceptable error range E. For the parameters of our proposed mechanism, we use $\tau_{min} = 0.2$ s and $\tau_{max} = 0.6$ s[1]. In addition, we use $a = 0.01$ and $b = 0.5$ for PRC in Eq. (3).

We conduct 100 simulations and evaluate the performance of our proposed mechanism in terms of *number of non-redundant sensor data*, *number of message transmissions*, and *data gathering delay*. The number of non-redundant sensor data is the average number of sensor data which is determined to be non-redundant and is gathered at the sink node in a cycle. The number of message transmissions is the average number of message transmissions on the whole WSN in a cycle. The data gathering delay is the average duration between the time that a cycle begins and the time that the sink node finishes receiving sensor data from the WSN in the cycle.

[1]In our simulation settings, the maximum number of neighbor sensor nodes is around 40. When we assume 20 ms is needed to send one message between sensor nodes as ODAS assumes, at least 0.8 s is needed for waking up to receive messages from all neighbor sensor nodes. In our mechanism, the wake-up duration of a sensor node is between $\tau_{max} + \tau_{min}$ and $2\tau_{max}$. In the case of above settings of offset, the wake-up duration satisfies 0.8 s.

To the best of our knowledge, there is no appropriate research work which considers sleep scheduling and data aggregation like our proposed mechanism. Therefore, we conduct simulation experiments for WAVE and ODAS in this paper for comparison purpose. In ODAS, we set the number of intermediate frames F at 2, and the number of data gathering frames G at the maximum hop number of the tree in the data gathering phase. The duration of a time slot is set as 20 ms. In addition, the optimal time slot assignment for all sensor nodes is attained in advance.

B. Evaluation of the number of non-redundant sensor data

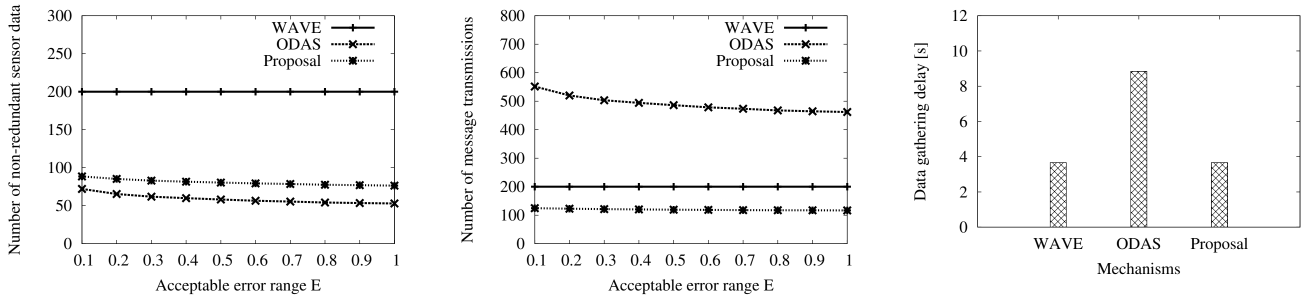
Figure 6(a) shows the number of non-redundant sensor data against the acceptable error range E. Since WAVE does not determine the redundancy of sensor data, all sensor data are gathered to the sink node regardless of the acceptable error range. On the other hand, both our proposed mechanism and ODAS can drastically reduce the number of non-redundant sensor data in comparison with WAVE because of their transmission reduction mechanism. For example, the number of non-redundant sensor data with our proposed mechanism is up to 61% lower than that with WAVE.

In both ODAS and our proposed mechanism, the number of non-redundant sensor data decreases when the acceptable error range increases, as shown in Fig. 6(a). This is because a larger number of sensor data satisfy the condition Eq. (2) when acceptable error range E becomes larger.

A comparison between our proposed mechanism and ODAS reveals that the number of non-redundant sensor data is between 22% and 44% larger with our proposed mechanism than with ODAS. This is because of the geographical difference of sensor data for determining redundancy, as described in Section IV-C. A sensor node in our proposed mechanism can use only downstream sensor nodes to determine the redundancy of sensor data whereas a sensor node in ODAS can use three sensor nodes whose locations construct a triangle containing the location of the sensor node. This situation in our proposed mechanism makes satisfaction of the condition Eq. (2) more difficult in the simulation experiments.

C. Evaluation of the number of message transmissions

Figure 6(b) shows the number of message transmissions against the acceptable error range. In Fig. 6(b), ODAS needs a much larger amount of message transmissions compared to WAVE and our proposed mechanism. From another viewpoint, the number of message transmissions in our proposed mechanism is up to 77% less than in ODAS. This is because in both WAVE and our proposed mechanism, sensor nodes broadcast a message only once in a cycle. On the other hand, in ODAS, some sensor nodes transmit messages in both the redundancy determination phase and the data gathering phase. In addition, ODAS assumes that each message contains a single sensor datum whereas a message in our proposed mechanism consists of more than one sensor datum. Therefore the number of message transmissions in ODAS becomes higher.



(a) Number of non-redundant sensor data. (b) Number of message transmissions. (c) Data gathering delay.

Fig. 6. Comparison among our proposed mechanism and conventional mechanisms.

A comparison between our proposed mechanism and WAVE reveals that the number of message transmissions in our proposed data gathering mechanism to be up to 41% less. This is because a sensor node with no transmission sensor data stops broadcasting messages. When we compare the number of non-redundant sensor data as shown in Fig. 6(a) and the number of message transmissions in our proposed mechanism as shown in Fig. 6(b), we see that the number of message transmissions is higher. This shows that some sensor nodes forward sensor data from downstream sensor nodes to upstream sensor nodes although their sensor data is determined to be redundant.

D. Evaluation of the data gathering delay

Figure 6(c) shows the data gathering delay for each mechanism. Here, the data gathering delay with both WAVE and our proposed mechanism is 58% lower than with ODAS. Since ODAS consists of two phases (i.e., the redundancy determination phase and the data gathering phase), its data gathering delay is larger than that of our proposed mechanism.

E. Discussion on energy efficiency

Finally, we discuss our proposed mechanism in terms of energy efficiency. When we compare our proposed mechanism and WAVE, we find that our proposed mechanism is more energy-efficient than WAVE since our proposed mechanism is based on WAVE while integrating measures to reduce transmissions.

On the other hand, when we compare our proposed mechanism and ODAS, we find that the number of message transmissions of our proposed mechanism is markedly lower although the number of non-redundant sensor data of our proposed mechanism is higher as described in previous sections. We should note that energy consumption generally increases with the number of message transmissions even if the total amount of sensor data is same because of overhead. In addition, when we consider ODAS-related overhead such as TDMA scheduling, time synchronization, and routing, we expect actual energy consumption would be much higher in a practicable ODAS situation. Furthermore, when we consider to apply some data aggregation / compression mechanisms to our proposed mechanism at the timing of message transmission, the size of message and energy consumption become much smaller. That is, we expect that our proposed mechanism is actually more energy-efficient than ODAS. We are planning to do an in-depth evaluation in terms of consumed energy to confirm the above discussion.

VI. Conclusions and Future Work

In this paper, we proposed an autonomous and energy-efficient data gathering mechanism with data transmission reduction for WSNs. To drastically reduce energy consumption, we integrated our data gathering mechanism and our data aggregation mechanism. Through simulation experiments, we confirmed that with our proposed mechanism, the number of message transmissions can be reduced by up to 77% compared to ODAS. However, we evaluated our proposed mechanism in an ideal environment. For example, we assume a fixed radio transmission distance, no sensing error, no localization error, etc. As for future research, an in-depth evaluation of our proposed mechanism within dynamic and unstable environments is needed.

Acknowledgments

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References

[1] L. Wang and Y. Xiao, "A survey of energy-efficient scheduling mechanisms in sensor networks," *Mobile Networks and Applications*, vol. 11, no. 5, pp. 723–740, Oct. 2006.

[2] Y. Taniguchi, N. Wakamiya, and M. Murata, "A traveling wave based communication mechanism for wireless sensor networks," *Journal of Networks*, vol. 2, no. 5, pp. 24–32, Sep. 2007.

[3] R. Rajagopalan and P. K. Varshney, "Data-aggregation techniques in sensor networks: A survey," *IEEE Communications Surveys and Tutorials*, vol. 8, pp. 48–63, 2006.

[4] C. Guestrin, P. Bodi, R. Thibau, M. Paski, and S. Madden, "Distributed regression: An efficient framework for modeling sensor network data," in *Proc. IPSN 2004*, Apr. 2004, pp. 1–10.

[5] T. Banerjee, K. Chowdhury, and D. P. Agrawal, "Distributed data aggregation in sensor networks by regression based compression," in *Proc. MASS 2005*, Nov. 2005, pp. 290–293.

[6] Y. Iima, A. Kanzaki, T. Hara, and S. Nishio, "Overhearing-based data transmission reduction for periodical data gathering in wireless sensor networks," in *Proc. DMIEW 2009*, Mar. 2009, pp. 1048–1053.

[7] J. Wang, R. K. Ghosh, and S. K. Das, "A survey on sensor localization," *Journal of Control Theory and Applications*, vol. 8, pp. 2–11, 2010.

[8] "Micaz datasheet," available at http://www.xbow.com/.

[9] P. Goel and B. Ermentrout, "Synchrony, stability, and firing patterns in pulse-coupled oscillators," *Physica D*, pp. 191–216, Mar. 2002.

[10] B. Sundararaman, U. Buy, and A. D. Kshemkalyani, "Clock synchronization for wireless sensor networks: a survey," *Ad Hoc Networks*, vol. 3, no. 3, pp. 281–323, May 2005.