Error-Tolerant Coverage Control based on Bio-inspired Attractor Selection Model for Wireless Sensor Networks

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***Abstract*—A coverage problem is one of major issues of a wireless sensor network to prolong the lifetime while guaranteeing that the target region and objects are monitored by sufficient number of active nodes. There have been many proposals on the coverage problem, but most of them use geometric algorithms in order to determine whether to monitor around or sleep. As such, these algorithms require information about the location, sensing area, and sensing state of neighbor nodes. In addition, they suffer from localization error leading to degradation of coverage and redundancy of active nodes. In this paper, we propose a coverage control mechanism where each sensor node relies only on the information about the degree of coverage of the target region. To enable autonomous decision of sensor nodes, we adopt a nonlinear mathematical model called the attractor selection model of adaptive behavior of biological systems to dynamically changing environment. Through simulation experiments, it is shown that the proposal outperforms the existing protocol regarding the per-node coverage and the overhead under influece of localization error.**

***Index Terms*—Wireless sensor networks, Coverage problem, Attractor selection model**

I. INTRODUCTION

Among a wide range of applications of wireless sensor networks (WSNs), surveillance, monitoring, and observation of items, objects, and regions are most promising and useful. These applications require that the sufficient number of nodes monitor the target region or objects. Since it is difficult to deploy and manage sensor nodes in an optimal manner, i.e. minimum number of nodes placed at the optimal positions, for the uncertainty and instability of location and sensing coverage, the redundant number of sensor nodes are distributed in the region to monitor. Then, a sophisticated sleep scheduling mechanism is employed to keep the number of active nodes as small as possible and let as many nodes as possible to sleep and save energy consumption, while satisfying application's requirements on the degree of coverage.

Such an issue to minimize the number of active nodes while guaranteeing the required coverage is called a coverage problem [1]. There have been many proposals on the coverage problem. Most of them, however, put unrealistic assumptions, e.g. accurate location and known perfect circular sensing area and as such they do not work well in the actual environment.

In this paper we propose a novel coverage maintenance protocol, which is free from the above-mentioned unrealistic assumptions. Each node does not need to know the shape and size of sensing area, the location of itself and neighbors, and the state of neighbors. A node relies only on the information about the degree of coverage of the target region. To enable autonomous decision of sensor nodes, we adopt a nonlinear mathematical model called the attractor selection model of flexible and adaptive behavior of biological systems to dynamically changing environment [2]. Through simulation experiments, it is shown that the proposal outperforms the existing protocol regarding the per-node coverage under influence of localization error and the overhead.

The remainder of this paper is organized as follows. First in section 2 we briefly discuss related work. Next, in section 3 we introduce the biological attractor selection model. Then, in section 4 we propose a novel coverage maintenance protocol adopting the attractor selection model. In section 5, we evaluate the proposal through comparison with CCP. Finally, in section 6, we conclude the paper.

II. RELATED WORK

There have been many proposals on the coverage problem, but most of them use geometric algorithms in order to estimate the degree of coverage for each sensor node to determine whether to be active or sleep. For example, CCP [3] adopts the so-called K_s-Eligibility algorithm. Based on the algorithm, a sensor node first obtains intersections of borders of sensing area of neighbor nodes in its sensing area and evaluate whether all of intersections in its sensing area are within sensing areas of the sufficient number of active nodes. Since CCP assumes the absolute location information and the identical sensing area of a circle of radius R_s on all sensor nodes, it suffers from errors in the location information and irregularity in the size and shape of sensing area. In addition, for a sensor node to evaluate the K_s-Eligibility rule, it has to obtain information about location, sensing area, and state of neighbor nodes at the sacrifice of bandwidth and energy in message exchanges. To increase the robustness against localization error, a location free coverage maintenance protocol is proposed in [4]. The protocol adopts the dominating set of the graph theory, but it requires a sensing area to be a circle and a transmission range to be adjustable. CARES [5] is another location-free protocol, where each sensor node stochastically and independently chooses its state based on the general Markov model. However, sensor nodes must be uniformly distributed in the monitored region and the shape of sensing area must be a circle. In an actual condition, a localization error could be as much as several meters [6] and the shape of sensing area is not a circle at all.

III. Attractor selection model

The attractor selection model imitates adaptive metabolic synthesis of bacteria to dynamically changing nutrient condition in the environment [2]. An attractor is a stable state where a nonlinear dynamic system reaches after an arbitrary initial state. A mutant $E.coli$ cell has a metabolic network consisting of two mutually inhibitory operons, each of which synthesizes different nutrient. When a cell is in the neutral medium where both nutrient sufficiently exist, mRNA concentrations dominating protein production are at the similar level. It means that a cell can live and grow in the environment independently of nutrient it synthesizes. Once one of the nutrients becomes insufficient in the environment, the level of gene expression of an operon corresponding to the missing nutrient eventually increases so that a cell can survive by compensating the missing nutrient. Although there is no embedded adaptation rule as a signal transduction pathway, a bacterial cell successfully adapts gene expression in accordance with the surrounding condition in this way.

In the attractor selection model, mRNA concentraions m_1 and m_2 for each nutrient synthesis change based on the equations below, respectively.

$$\frac{dm_1}{dt} = \frac{S(A)}{1+m_2^2} - D(A)m_1 + \eta_1 \tag{1}$$

$$\frac{dm_2}{dt} = \frac{S(A)}{1+m_1^2} - D(A)m_2 + \eta_2 \tag{2}$$

A is the cellular activity such as growth rate and expresses the goodness of the current behavior, i.e. the state of gene expression. Functions $S(A)$ and $D(A)$ are rate coefficients of mRNA synthesis and decomposition, respectively. In [2], $S(A) = \frac{6A}{2+A}$ and $D(A) = A$ are used. η_i $(i = 1, 2)$ corresponds to internal and external noise or fluctuation in gene expression.

Now let us explain the dynamics of mRNA concentrations. When the activity is high, the nonlinear dynamic system formulated by the above equations has one attractor where $m_1 = m_2 = m^*$. Here, m^* is a constant and larger than one. Therefore, a cell stays at the attractor and generates either of two nutrient when the sufficient nutrients are available and it grows well. When the activity becomes low, there appears two attractors, i.e. $m_1 = m^*$ and $m_2 = 1/m^*$ or $m_1 = 1/m^*$ and $m_2 = m^*$, where either of mRNA concentrations is higher than the other. Since the first two terms of the right side of Eqs. (1) and (2) are multiplied by the activity, potential of attractors becomes shallow and the dynamics is dominated by the noise terms. Consequently, m_1 and m_2 change at random. When the mRNA concentration, i.e. m_1 or m_2, of the missing nutrient occasionally becomes large, the activity slightly increases as a cell can live better. The increase in the activity makes the potential of attractor deeper and the state of cell moves toward the attractor by entrainment. The activity further increases accordingly and the influence of noise becomes smaller. Eventually the state of a cell reaches an appropriate attractor and stays there stably as far as the nutrient condition does not change.

The attractor selection model is one of metaheuristics to find an optimal solution under some criteria. In the model, the solution space is defined by temporal differential equations and attractors are possible solutions. The objective to maximize is expressed as an activity. In the biological case, a bacteria adaptively chooses one of solutions, i.e. synthesis of either of two nutrients, so that it can maximize the growth rate according to the environmental nutrient condition. In our application of the attractor selection model to coverage control, a node chooses one of two states, i.e. sleep or active, to maximize the global activity defined by the coverage of the target region.

IV. Attractor selection-based coverage control

In this section, we first outline basic behavior of our proposal. Then, we describe the attractor selection model adopted in our proposal and the definition of activity in coverage control. Finally, we describe detailed behavior of nodes in our proposal.

A. Overview of our proposal

In this paper we consider a periodic monitoring application, where a sink collects sensing data from sensor nodes at regular intervals. We refer to the beginning of data gathering as $timing\ of\ data\ gathering$. We denote the duration between two successive timings of data gathering as $cycle$, whose length is the same as the data gathering interval.

At each timing of data gathering, each sensor node which was active in the preceding cycle transmits a message to a sink by single or multi-hop communication. Since in this paper our focus on coverage control, we do not assume any specific data gathering mechanisms to collect messages from nodes. We also assume that the connectivity is maintained when the sufficient coverage is achieved [3]. A message consists of sensing data and the information for a sink to estimate the degree of coverage of the target region. From received messages, a sink evaluates the coverage of the target region. The way that the coverage is evaluated depends on the requirement of application. When any localization mechanism is available at sensor nodes, the coverage is estimated based on the relative or absolute location of nodes. An identifier of objects that a sensor node monitors is also useful information when a sink knows locations of the objects in the target region. From the coverage, a sink derives the activity, i.e. a scholar value reflecting the goodness of coverage condition.

A sink then disseminates the activity information over a wireless sensor network by using any efficient dissemination mechanism. Not only sensor nodes that are active in the preceding cycle but sensor nodes whose sleep timer expires at

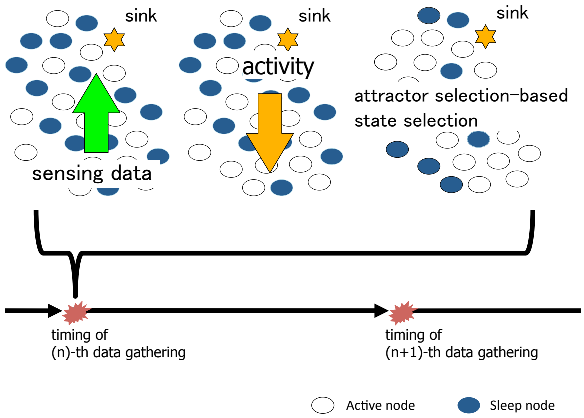


Fig. 1. Overview of proposal

the timing of data gathering receive the activity information. Sensor nodes receiving the activity information then decides whether to be active or sleep following mechanisms described below. If a sensor node decides to be active, it starts sensing its surroundings. Otherwise, a sensor node sets a sleep timer at a multiple of data gathering interval and sleep immediately.

B. Extended attractor selection model

In our proposal, we use the following attractor selection model, introduced in [7] for adaptive ad-hoc network routing.

$$\frac{dm_1}{dt} = \frac{syn(\alpha)}{1+m_2^2} - deg(\alpha)m_1 + \eta_1 \quad (3)$$

$$\frac{dm_2}{dt} = \frac{syn(\alpha)}{1+m_1^2} - deg(\alpha)m_2 + \eta_2 \quad (4)$$

and

$$syn(\alpha) = \alpha \times (\beta \times \alpha^{\gamma} + \varphi^*) \quad (5)$$

$$deg(\alpha) = \alpha \quad (6)$$

This model has two attractors, i.e. $m_1 > m_2$ or $m_1 < m_2$. β $(0 < \beta)$ is a parameter related to the stability of attractor and γ $(0 < \gamma < 1)$ is a parameter related to the speed of convergence. φ^* is a constant for the dynamic system to have stable attractors and we use $1/\sqrt{2}$. Activity α is derived by the following temporal differential equation from the instant activity α^* $(0 \leq \alpha^* \leq 1)$.

$$\frac{d\alpha}{dt} = \delta \times (\alpha^* - \alpha) \quad (7)$$

Instant activity α^* is derived from the degree of coverage and its derivation will be explained in the next section. δ corresponds to the rate of response to the instant activity. When δ is small, e.g. 0.01, the activity would not be affected by temporal fluctuation in the instant activity and we can expect the stable coverage control at the sacrifice of the speed of adaptation and convergence.

C. Derivation of instant activity

Although any form of coverage estimation can be applied to coverage control in our proposal as stated above, in this paper we consider the following derivation for the sake of easy implementation and comparison. We define the instant coverage by the fraction of target region monitored by the sufficient number of active nodes. More specifically, the target region is first divided into small regions of 1 [m] $\times$ 1 [m], called a patch.

When we indicate a patch by its virtual coordinate (x, y) where $1 \leq x \leq x_{max}$ and $1 \leq y \leq y_{max}$ in the target region of x_{max} [m] $\times$ y_{max} [m], the coverage $CoP(x, y)$ of patch (x, y) is approximated by the number of active nodes that has a center of patch (x, y) in its sensing area. When an application requires an arbitrary point of the target region to be monitored by k active nodes, called k-coverage, the sensing ratio S $(0 \leq S \leq 1)$ of the whole region is derived by the following equation.

$$S = \frac{\left|\{(x, y) \mid CoP(x, y) \geq k\}\right|}{P_{all}} \quad (8)$$

We can also define the sensing ratio per small areas of the target region for fine-grained control. In this case, the target region is divided into sub-areas of x_{sub} [m] $\times$ y_{sub} [m], where x_{sub} and y_{sub} are divisors of x_{max} and y_{max}, respectively. Each small area has virtual coordinates (x_{area}, y_{area}) where $1 \leq x_{area} \leq x_{max}/x_{sub}$ and $1 \leq y_{area} \leq y_{max}/y_{sub}$ and the sensing ratio $S(x_{area}, y_{area})$ of small area (x_{area}, y_{area}) is derived by the following equation.

$$\begin{aligned} S(x_{area},y_{area}) = &\ |\{(x,y)|CoP(x,y) \geq k \\ \wedge &\ (x_{area}-1) \times x_{sub} + 1 \leq x \leq x_{area} \times x_{sub} \\ \wedge &\ (y_{area}-1) \times y_{sub} + 1 \leq y \leq y_{area} \times y_{sub}\}| \\ / &\ (x_{sub} \times y_{sub}) \end{aligned} \quad (9)$$

Since the sensing ratio does not take into account the redundancy in monitoring where a patch is in the sensing area of more than k active nodes, using S as α^* in Eq. (7) leads to waste of energy. Therefore, we formulate redundancy ratio R $(1 \leq R)$ for the whole region and the sub area (x_{area}, y_{area}) as,

$$R = \frac{\sum_{i=1}^{x_{max}} \sum_{j=1}^{y_{max}} Z(CoP(i,j))}{\left|\{(x, y) \mid CoP(x, y) \geq k\}\right|} \quad (10)$$

$$R(x_{area},y_{area}) = \frac{\sum_{i=(x_{area}-1)\times x_{sub}+1}^{x_{area}\times x_{sub}} \sum_{j=(y_{area}-1)\times y_{sub}+1}^{y_{area}\times y_{sub}} Z(CoP(i,j))}{\left|\{(x, y) \mid CoP(x, y) \geq k\}\right|} \quad (11)$$

and

$$Z(x) = \begin{cases} x - k + 1 & (x \geq k) \\ 0 & (x < k) \end{cases} \quad (12)$$

Then, instant activity α^* is derived for the whole region as,

$$\alpha^* = \left(\frac{S}{\max\{1, w \times R\}}\right)^p \quad (13)$$

Weight w $(0 < w \leq 1)$ determines concerns about the redundancy and a larger w leads to more efficient control. Power p $(1 \leq p)$ regulates the influence of fluctuation in the sensing ratio and the redundancy ratio to the instant activity. Operator $\max$ is introduced to prevent the instant activity from exceeding one. We call the activity derived using the instant activity in Eq. (13) as the global activity. In case of sub-area based control, instant activity $\alpha^*(x_{area}, y_{area})$ of the sub-area (x_{area}, y_{area}) is given as,

$$\alpha^*(x_{area}, y_{area}) = \left(\frac{S(x_{area}, y_{area})}{\max\{1, w \times R(x_{area}, y_{area})\}}\right)^p \quad (14)$$

The activity derived by Eq. (14) is called the area activity. In the case of area activity-based control, a sink evaluates all area activities $\alpha(x_{area}, y_{area})$ by substituting $\alpha^*(x_{area}, y_{area})$ in Eq. (7) and a message disseminated by a sink contains all area activities. A sensor node uses the area activity of a small area in which the node considers to be located. It implies that a node with location information with errors uses the area activity of a wrong sub-area.

D. Node behavior

Each node which receives the activity information evaluates equations in section IV-C. to update m_1 and m_2 by using the appropriate activity, i.e. the global activity in the global activity-based control and the corresponding area activity in the area activity-based control. Then, it determines its next state. More specifically, a sensor node which was active in the preceding cycle behaves as follows at the timing of data gathering.

- Step1 Sensor node transmits the sensing data to the sink.
- Step2 Sensor node receives the activity information from the sink.
- Step3 Sensor node evaluates the attractor selection model with received activity and update m_1 and m_2.
- Step4 In case of $m_1 > m_2$, a node remains active and keeps monitoring in the following cycle.
  In case of $m_1 \leq m_2$, a node sets sleep timer as a multiple of data gathering interval by l to wake up at the timing of data gathering and turns off all other modules to sleep. l $(1 \leq l)$ is a control parameter. To avoid synchronous behavior of nodes, l is set at random.

A sensor node which wakes up at the timing of data gathering for expiration of sleep timer follows the steps below.

- Step1 Sensor node receives the activity information from the sink.
- Step2 Sensor node evaluates the attractor selection model with received activity and update m_1 and m_2.
- Step3 In case of $m_1 > m_2$, a node turns active and starts monitoring in the following cycle.
  In case of $m_1 \leq m_2$, a node sets sleep timer as a multiple of data gathering interval by l to wake up at the timing of data gathering.

V. SIMULATION EXPERIMENTS

In this section we first briefly explain CCP used for comparison and then error models, i.e. localization error and shape error, are introduced. Simulation results follow to compare the proposal with CCP in terms of the sensing ratio, number of active nodes, redundancy ratio, contribution ratio, and overhead. In addition, we estimate the degree of coverage in the presence of the errors in sensing area.

A. CCP (Coverage Configuration Protocol)

CCP [1], [3] is the coverage control protocol which uses the geometric algorithm. It assumes that the absolute location information is available on each node and the identical and circular sensing area of radius R_s. There are two main states, i.e. ACTIVE and SLEEP, and three intermediate states, i.e. LISTEN, JOIN, and WITHDRAW to avoid conflict in state transition. There are three messages, i.e. HELLO, JOIN, and WITHDRAW, to exchange state information.

An ACTIVE node periodically broadcasts a HELLO message to notify neighbor nodes of its ACTIVE state and location. Receiving a message of any type, a node evaluates the so-called K_s-Eligibility algorithm. A node first calculates all intersections of two neighboring ACTIVE nodes or one neighboring node and the border of the target region. If all intersections inside its sensing area are within sensing areas of K_s or more ACTIVE nodes except for itself, the algorithm returns false, indicating that the node is eligible to sleep. Otherwise, it returns true and the node has to keep awake and monitor the surroundings.

In the case of false, a node first moves to the WITHDRAW state for the interval of WITHDRAW timer to confirm its eligibility. It keeps evaluating the K_s-Eligibility algorithm whenever it receives a message. Once it obtains true, it cancels the timer and goes back to the ACTIVE state. When the timer expires, it broadcasts a WITHDRAW message and moves to the SLEEP state while setting the SLEEP timer. When the SLEEP timer expires, a node moves to the LISTEN state setting the LISTEN timer. As in the WITHDRAW state, it evaluates the K_s-Eligibility algorithm. If the algorithm returns true on message reception, it moves to the JOIN state and starts the JOIN timer. Otherwise, the LISTEN timer expires and it goes back to the SLEEP state silently. In the JOIN state, a node keeps evaluating the K_s-Eligibility algorithm. When the algorithm returns false, it goes back to the SLEEP state silently. When the JOIN timer expires, the node broadcasts the JOIN message and moves to the ACTIVE state. For further details, refer to [3].

B. Localization error

Based on [8], we consider a simple model of localization error. The amount of error is uniformly distributed between $-u$ and u, where u is the maximum error in meter. The erroneous coordinates of a sensor node at geographical coordinates (x, y) is given at random in the area of $(x-u, y-u)$ as the left bottom corner and $(x+u, y+u)$ as the right top corner.

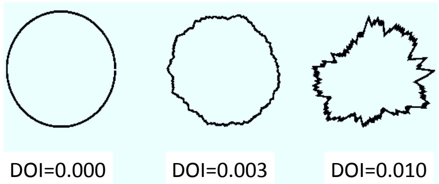


Fig. 2. Irregular sensing area

In our proposal, a sink evaluates the global or area activity with wrong location information received from nodes. Then, the activity notified to nodes is different from the actual activity. On the other hand, a sensor node with CCP calculates intersections of sensing areas based on wrong location information. Then, the K_s-Eligibility algorithm would return a wrong answer. In the case of CCP, an intersection considered to be out of the target region is assumed to be covered by K_s active nodes.

C. Shape error

Since there is no model of irregular sensing area, we adopt the model of radio propagation irregularity introduced in [9]. RIM (Radio Irregularity Model) models the variation in the received signal strength under the influence of heterogeneous energy loss. In wireless communication, the signal strength decreases in accordance with the distance. The following is the commonly used model to estimate path loss L.

$$L\ [\text{dBm}] = C + 10n \log_{10} d \tag{15}$$

Here, C is a constant and n expresses the quality of transmission path. Parameter d is the distance between the transmitter and the receiver. Then, RIM introduces the irregularity in path loss as,

$$R = S - DOIAdjustedPathLoss + F \tag{16}$$

$$DOIAdjustedPathLoss = L \times K_i \tag{17}$$

R represents the received signal strength and S corresponds to the transmission power. F corresponds to the fading effect. K_i implements the difference in path loss at the i_{th} degree and given by the following equation.

$$K_i = \begin{cases} 1\ ,\ i = 0 \\ K_{i-1} \pm r \times DOI,\ 0 < i < 360\ \wedge\ i \in N \end{cases} \tag{18}$$
$$where\ |K_0 - K_{359}| \leq DOI$$

Parameter DOI (Degree of irregularity) is the coefficient of irregularity. r is a random number following the Weibul distribution.

For example, we depict the impact of different DOI in Fig. 2. Each shape shows the border of region where the received signal strength exceeds a certain threshold. As can be seen, $DOI = 0$ gives a circular shape. As DOI increases, the shape becomes more irregular. We first set parameters appropriately to obtain the regular circle shape of the desired sensing radius and then change DOI to see the influence of irregularity in the experiments.

D. Simulation setting

10000 sensor nodes are randomly deployed in the target region of 500 [m] $\times$ 500 [m]. In the case that the area activity is used, the target region is divided into sub-areas of 25 [m] $\times$ 25 [m]. An applications requires 1-coverage ($K_s = k = 1$) and periodic data gathering at intervals of 10 [s]. We assume that in data gathering and message dissemination, one message is transmitted per node. Such ideal communication can be accomplished by a tree-based routing or a broadcasting-based mechanism such as [10]. In the following figures, averages over 50 simulation runs are shown.

At the beginning of a simulation run, all nodes are active. In our proposal, both m_1 and m_2 are initialized to one and the initial activity is zero. Parameter β is 2.5 and parameter γ is 1.2. Parameter δ is 0.01. Weight w is 0.5 and power p is 1. The number l of cycles of sleep in our proposal is randomly chosen with an average of three. In CCP, HELLO interval, SLEEP, WITHDRAW, JOIN, and LISTEN timers are set at 2 [s], 10 [s], 5 [s], 5 [s] and 2 [s], respectively.

The communication range is set at 20 [m]. The shape of sensing area is a circle of radius $R_s = 10$ [m] and identical among nodes under the condition without shape error. In our proposal, a sink assumes the circular sensing area and believes the location information reported by sensor nodes in derivation of the activity. In CCP, intersections are calculated assuming the circular sensing area and the errorless localization. For evaluation of tolerance to localization error, we change the maximum location error u from 0 [m] to 10 [m], e.g. GPS-based localization. For evaluation of tolerance to shape error, we change DOI from 0 to 0.03.

As performance measures, we use the sensing ratio S, number N of active nodes, redundancy ratio R, contribution ratio B, and overhead O. Contribution ratio B indicates the degree of contribution of an active node to coverage and is derived as $B = 500\ [\text{m}] \times 500\ [\text{m}] \times S/N\ [\text{m}^2]$. Therefore, the contribution ratio is the average area that an active node is responsible for monitoring. The larger the contribution ratio is, more cost effective is sensing. Overhead O corresponds to the number of message transmissions involved in coverage control and data gathering. In our proposal, since there is no message exchanges among nodes to obtain information about neighbors, messages are transmitted only for data gathering and message dissemination. Therefore, the overhead per cycle is the N for data gathering and $N + N'$ for message dissemination where N' corresponds to the number of nodes waking up at timing of data gathering. On the other hand, in CCP, under the stable condition only nodes in the ACTIVE state transmit messages, i.e. HELLO message. Since the target region is well covered by those active nodes, sensor nodes in the LISTEN state always go back to the SLEEP state without message emission and no node moves to the SLEEP state via the WITHDRAW state. Therefore, the overhead of CCP can be approximated as sum of $N \times$ (data gathering interval/HELLO interval) for HELLO message exchanges and N for data gathering.

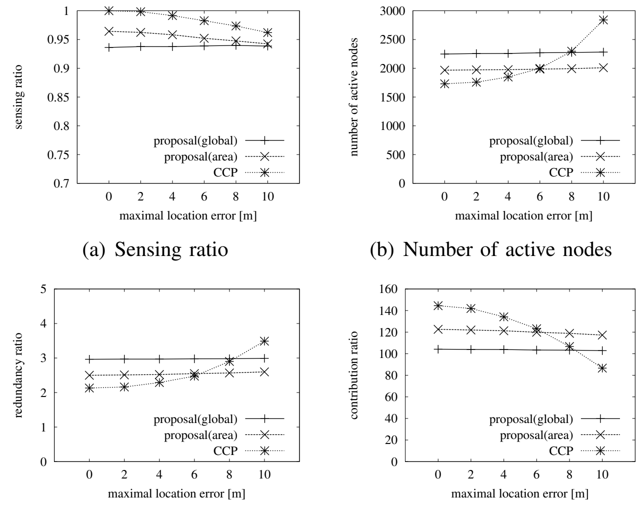
E. Evaluation of error-tolerance

First we compare CCP and two variants of our proposal, i.e. the global activity-based control and the area activity-based control, under the influence of localization error. DOI is set at zero. Figure 3(a) shows the average sensing ratio against different localization errors. When there is no localization error, CCP achieves the perfect coverage for its geometric and deterministic algorithm. However, the sensing ratio gradually decreases as the localization error becomes large. On the other hand, for the ambiguity of contribution of each node to the coverage, it is hard for our proposal to achieve the maximum coverage. In our proposal, each node selects its state autonomously and independently from others. Therefore, there is more chances that multiple sensor nodes change their state simultaneously, especially when the activity is low and sensor nodes are driven by noise. Under such condition, a node cannot judge whether the increase or decrease of the activity is caused by its state change or not. Therefore, the optimal and deterministic state selection is not possible. However, since our proposal does not rely on the certainty of information, it suffers from the localization error less than CCP. In the figure, the global activity-based control keeps its coverage against different degree of localization error. The area activity-based control achieves higher sensing ratio than the global activity-based control by having more direct interaction among nodes, where state change of a node directly influences the area activity more than the global activity. However, it spoils the independence of the proposal on the accurate location information. As such, the sensing ratio decreases with the area activity-based control.

Despite for lower sensing ratio, Fig. 3(b) proves the robustness of our proposal against the localization error. On the contrary to CCP which requires more and more active nodes to maintain the high sensing ratio, the number of active nodes does not change much with our proposals.

The increased number of active nodes with CCP affects the redundancy ratio as shown in Fig. 3(c). The redundancy ratio is about 10 when all nodes are active in our simulation setting. Without localization error, the redundancy ratio is reduced to about 2 or 3, where the redundant nodes are successfully allowed to sleep. A reason why the redundancy ratio does not decrease as low as one is that sensing areas overlap with each other and even for a small void of 1 [m^2], a node has to be awake if it is a only node that can cover the void. The redundancy ratio increases with CCP as the localization error increases.

To evaluate the efficiency of coverage control, Fig. 3(d) illustrates the contribution ratio B against different localization errors. Although the sensing area of each node is about 314 [m^2], the contribution ratio is as high as 144 [m^2] for overlapping. As can be expected from Figs. 3(a) and 3(b), the contribution ratio of CCP decreases as the localization error increases. With the localization error of 6 or more meters, the area activity-based control accomplishes more efficient coverage control than CCP.



(a) Sensing ratio (b) Number of active nodes

(c) Redundancy ratio (d) Contribution ratio

Fig. 3. Simulation result (error-tolerance)

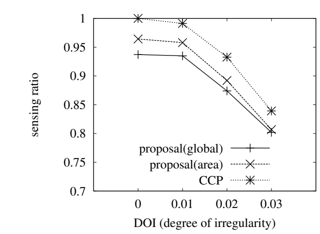


Fig. 4. Sensing ratio with shape error

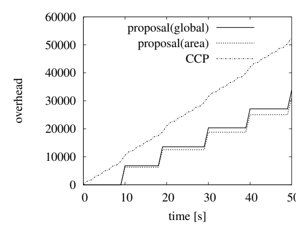
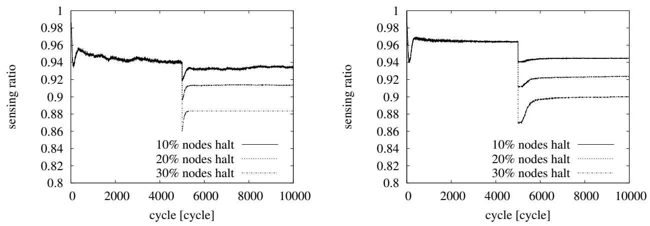


Fig. 5. Overhead

Figure 4 shows the influence of shape error on the sensing ratio, where there is no localization error. As shown in the figure, the sensing ratio of all of the global activity-based control, the area activity-based control, and CCP decreases. When there is the shape error, a patch considered to be within a circular sensing area of an active node is not necessarily covered by an actual sensing area. Although a patch out of a circular sensing area of an active node could be covered by a distant active node for irregularity of sensing area, another active node is made to be active to cover the patch with coverage control. Therefore, the shape error mainly decreases the sensing ratio. When there is the shape error, a patch considered to be within a circular sensing area of an active node is not necessarily covered by an actual sensing area. Although a patch out of a circular sensing area of an active node could be covered by a distant active node for irregularity of sensing area, another active node is made to be active to cover the patch with coverage control. Therefore, the shape error mainly decreases the sensing ratio.

Finally, Fig. 5 compares the average overhead during 50 [s] simulation time after 10000th cycle and 100 [s] in our proposal and CCP, respectively. In our proposal, bursty transmission is observed every 10 [s]. From Fig. 3(b), the number of active nodes is about 2000 to 2300, i.e. $N = 2000$ to 2300. Among 8000 to 7700 sleeping nodes, one third would wake up at



(a) Proposal (global) (b) Proposal (area)

Fig. 6. Simulation result (adaptability)

timing of data gathering, i.e. $N^{'} = 2600$ approximately. Then, $2N + N^{'}$ amounts to about 6000 to 7000. On the other hand, about 1700 active nodes broadcast HELLO messages every 2 [s] and transmit sensing information every 10 [s] in CCP. This corresponds to about 1000 messages per second. Although it is possible to decrease the overhead of CCP with a longer HELLO interval, it causes the extra energy consumption. The timers for the intermediate states, i.e. LISTEN, JOIN, and WITHDRAW must be long enough and proportional to the HELLO interval to receive the sufficient number of message so that a node confirms its eligibility. With a longer HELLO interval, nodes are forced to be awake for a longer duration of time. Consequently, they consume more energy.

F. Evaluation of adaptability

In this section, we evaluate the adaptability of the proposal against failure of sensor nodes. At the end of 5000th timing of data gathering, we stop randomly chosen 10%, 20%, or 30% of active nodes. In Fig. 6, time variation of sensing ratio is depicted. When 10% of active nodes die, the sensing ratio first decreases from 0.938 to 0.919 in the case of the global activity-based control. Then, the sensing ratio is gradually recovered to 0.934 at 10000th timing of data gathering, that is, 99.5% of the coverage ratio before failures. In the case of 20% and 30% failures, the degree of recovery is 97.3% and 94.1%, respectively. When the area activity is used, the degree of recovery decreases to 97.8%, 95.7%, and 93.3% for 10%, 20%, and 30% failures, respectively. However, there still exists room for improvement, which remains as future work. For example, with a larger p, we can keep the activity low unless the sensing ratio is sufficiently high and the redundancy ration is small enough. With $p = 3$ and $w = 0.4$ in the area activity-based control, more than 99.0% recovery can be accomplished independently of degree of failures, while keeping the redundancy ratio as low as about 2.2.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, by adopting the attractor selection model of adaptive behavior of biological systems, we proposed an error-tolerant coverage control method and showed the proposal outperformed CCP in the contribution ratio under localization error and the overhead through simulation experiments. However, our proposal cannot guarantee the sensing ratio of one as the state selection is modeled by stochastic differential equations, i.e. non-deterministic algorithm. Furthermore, our proposal takes time to find a new better solution as shown in Fig. 6.

As future research, we plan to improve the performance of proposal in terms of the coverage ratio and the speed of convergence. For example, the higher sensing ratio can be accomplished by changing Eq.(13) so that the activity stays low for the insufficient sensing ratio S. We can also have the faster convergence by strengthening the entrainment or having the deeper basin of a good attractor by refining equations. However, there is a trade-off between these two. We are now considering this issue.

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