Error-tolerant and energy-efficient coverage control based on attractor selection model for wireless sensor networks

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1 Introduction

For surveillance and monitoring applications, it is necessary to minimize the number of nodes engaged in monitoring while guaranteeing the required coverage to save energy consumption and prolong the lifetime of a wireless sensor network. This issue is called a coverage problem [1]. To accomplish the goal, most existing protocols employ geometric algorithms by assuming that each node knows the exact location and the shape and size of sensing area. For example, in CCP [2], a node first derives intersections of borders of sensing areas of neighbor nodes in its sensing area and evaluates whether all of intersections in its sensing area are within sensing areas of the sufficient number of active nodes. The actual environment, however, does not satisfy such unrealistic assumptions and thus they cannot provide the sufficient performance.

In [3], we proposed a novel coverage maintenance protocol, which is free from above-mentioned unrealistic assumptions. Each node relies only on the information about the degree of coverage of the target region. To enable autonomous decision of nodes, we adopted the attractor selection model of flexible and adaptive behavior of biological systems to dynamically changing environment [4]. Simulation experiments proved that the proposal outperforms CCP regarding the per-node coverage under influence of localization error with much less overhead. In this paper, we further consider the aspect of energy efficiency, which is one of major concern of wireless sensor networks, by using the energy consumption model of an off-the-shelf node device.

2 Attractor selection based coverage control

We assume an application where a sink periodically collects sensing data from all nodes engaged in monitoring. Each node has three operating states, i.e. active, sleep, and intermediate and maintains two values m_1 and m_2, called state values, to determine the state based on the attractor selection model. At the timing of data gathering, nodes in the active state send sensing data toward the sink and moves to the intermediate state. Nodes which wake up at the timing also enter the intermediate state. The sink evaluates the degree of coverage and disseminates this information over the network. Nodes in the intermediate state receive the feedback message, evaluate attractor selection equations, and decide the next state.

Active state: A node monitors its sensing area by turning and keeping sensor modules on and transceiver modules off for the fixed period I_s of time, called sensing interval. When the timing of data gathering arrives, a node turns on transceiver modules and sends sensing data toward the sink. Then, it moves to the intermediate state.

Sleep state: A node turns and keeps all modules off to save battery. When a sleep timer expires, a sensor node turns transceiver modules on and moves to the intermediate state.

Intermediate state: A node waits for a feedback message from the sink during the fixed period I_w of time, called intermediate interval. The feedback message contains value α, called activity, which reflects the degree of coverage. On reception, a node updates state values m_1 and m_2 using the following equations of the attractor selection model. Due to space limitation, please refer to [3] for details.

$$\frac{dm_{\{1,2\}}}{dt} = \frac{\alpha \times (\beta \times \alpha^{\gamma} + \varphi^{*})}{1 + m_{\{2,1\}}^{2}} - \alpha \times m_{\{1,2\}} + \eta_{\{1,2\}} \quad (1)$$

where β ($\beta > 0$) and γ ($\gamma > 1$) are parameters related to the stability and convergence, respectively. φ^{*} is a constant and $1/\sqrt{2}$. In case of $m_1 > m_2$, the node transits to the active state. Otherwise, it sets the sleep timer at $I_s + l \times (I_s + I_w)$. l ($l \geq 0$) is a parameter, which is randomly chosen following the uniform distribution between 0 and 4. Then, it moves to the sleep state. The sum of sensing interval and intermediate interval is equal to the length of the duration between successive timings of data gathering.

The activity is derived at the sink on receiving sensing data. To derive the activity, the sink first evaluates the sensing ratio S_k, which indicates the ratio of area covered by more than k nodes in the active state. k is specified by an application with respect to the required degree of coverage. For the sake of simplicity, we empirically approximate S_k. First, the target region is divided into small regions of, e.g. 1 [m] $\times$ 1 [m], called a patch. When the center of a patch located at (x, y) is in the sensing region of n node in the active state, we consider the coverage

$C(x, y)$ is n. Then, the sensing ratio is derived as $S_k = |\{(x, y) \mid C(x, y) \geq k\}|/P_{all}$ $(1 \geq S_k \geq 0)$, where P_{all} corresponds to the number of patches.

To take into account the redundancy and deficiency in coverage, we further introduce another measure, i.e. the excess and deficiency ratio E_k, which is derived as $E_k = \sum_{i=1}^{x_t} \sum_{j=1}^{y_t} |C(i, j) - k|/P_{all} + 1$ $(E_k \geq 1)$.

Finally, activity α is derived as

$$\alpha = \left(\frac{S_k}{\max\{1, w \times E_k\}}\right)^p \quad (2)$$

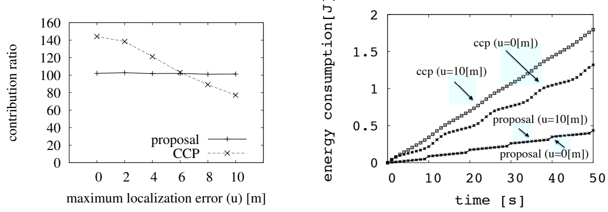
Weight w $(1 \geq w > 0)$ is a control parameter, where a larger w contributes to more efficient coverage control. Power p $(p \geq 1)$ is used for scaling.

3 Simulation evaluation

10000 nodes are randomly deployed in the target region of 500 [m] × 500 [m] and one sink is placed in the center of the target region. Geographical coordinates that a node has contain error which is uniformly distributed between $-u$ and u, where u [m] is the maximum error. In our proposal, localization error affects the sensing ratio estimated at the sink. In CCP on the other hand, each node uses erroneous coordinates in evaluating the coverage of its sensing area. Communication range is set at 20 [m]. The shape of sensing area is a circle of radius 10 [m]. An application requires 1-coverage $(k = 1)$ and periodic data gathering at intervals of 10 [s]. In our proposal, parameters are set as $\beta = 2.5$, $\gamma = 1.2$, $w = 0.5$, and $p = 1.0$. Sensing interval I_s is 9 [s] and wakeup interval I_w is 1 [s].

We define the energy model based on MICAz [5]. CPU consumes 8 [mA] (on) or 15 [uA] (off). A transceiver module consumes 19.7 [mA] in listening a channel and receiving a message and 17.4 [mA] in transmitting a message. A sensor module consumes 10 [uA] (on) or 0 [uA] (off). We assume an appropriate tree-based routing protocol and complete data aggregation. In data gathering, a node receives sensor data from its child nodes, generates the aggregated data of the same size of a single sensor data, and sends it to a parent node. In disseminating feedback messages, a node receives a message from its parent and forwards it to all child nodes.

Fig. 1(a) illustrates the contribution ratio against the maximum localization error. *Contribution ratio* is defined as 500 [m] × 500 [m] × S_k/N, where N is the number of nodes in the active state. When there is no or small localization error, CCP achieves the higher contribution ratio than our proposal. However, since CCP relies on the deterministic seometric algorithm, the contribution ratio decreases as the maximum localization error increases. On the contrary, the contribution ratio of our proposal does not change much,



(a) Contribution ratio (b) Energy consumption

Figure 1 Simulation result (avg. of 10 runs)

because selection of states at a node does not rely on location information of itself and neighbors.

Fig. 1(b) shows the average energy consumption per node against time for cases with and without localization error. Results of our proposal with and without localization error overlap with each other. It is apparent that our proposal consumes only one forth or one third energy of CCP. It is because that CCP consumes energy in information exchanges and state transitions, whereas our proposal does not involve any additional communication among nodes for coverage control. Furthermore, CCP consumes more energy with larger localization error for requiring more nodes in the active state. In summary, our proposal is more robust against localization error and more energy efficient than CCP.

4 Conclusion

In this paper, we showed our coverage control protocol is superior to CCP in terms of the error tolerance and energy efficiency.

Acknowledgement

This research was supported in part by "Global COE Program" of MEXT, Japan and "Early-concept Grants for Exploratory Research on New-generation Network" of NICT, Japan.

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