A Bio-Inspired Scheduling Scheme for Wireless Sensor Networks

Chi-Tsun Cheng, Chi K. Tse and Francis C. M. Lau
Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hong Kong
URL: http://chaos.eie.polyu.edu.hk

***Abstract*— Sensor networks with a large amount of sensor nodes usually have high redundancy in sensing coverage. The network lifetime can be further extended by proper scheduling and putting unnecessary sensor nodes into sleep mode. In this paper a bio-inspired scheduling scheme is proposed. The proposed scheme is a kind of adaptive "selective on-off" scheduling scheme which uses only local information for making scheduling decisions. The scheme is evaluated in terms of target 3-coverage hit-rate, averaged detection delay, and energy consumption per successful target detection. Simulation results show that our proposed scheme can reduce energy consumption by as much as 2/3 when comparing with other generic scheduling schemes while maintaining the detection delay and target hit-rate at a comparable level. Optimization of the network lifetime and other performances is possible by adjusting some parameters.**

Keywords: bio-inspired, scheduling, soft deployment, task switching, wireless sensor networks.

I. Introduction

Advanced electronic technology allows the manufacture of compact and versatile wireless sensor nodes. Sensor networks with hundreds to thousands of sensor nodes are used to monitor essential phenomena which are difficult to access or require a prolonged period of observation. With sensors placed close to a phenomenon, sensor networks can capture data in high resolution even with low cost sensors. The large volume of sensor nodes also provides redundancy in sensing which makes sensor networks highly robust when compared with traditional sensing systems.

Two basic problems, among others, with the implementation of sensor networks are related to power limitation and interference. First, since sensor nodes are battery powered and sensing fields are usually inaccessible for battery replacement, energy conservation becomes a critical issue in sensor networks. Second, the large amount of sensor nodes will also cause severe interference especially in region where sensor nodes are densely populated. Some kinds of scheduling scheme should be employed to increase the bandwidth efficiency.

Both problems can be solved by switching off part of the network. However, nodes to be switched off cannot be arbitrary chosen. Having too few active sensor nodes will cause reduced sensing field coverage, long detection delay and poor tracking of target. On the other hand, having excessive active sensor nodes will reduce network lifetime and introduce excessive interference. Active sensor nodes should be distributed as close to the phenomenon as possible so that the system can provide the highest sensing quality with the minimum number of sensor nodes. Scheduling, which is also known as soft deployment, is a process of maintaining a balance among energy saving, bandwidth efficiency and sensing quality.

Scheduling can be classified into four main categories. They are "always on", "random on-off", "selective on-off" and "periodic on-off" [1]. All sensors will stay active throughout their lifetime when "always on" scheduling is employed. With the highest redundancy in sensing field coverage, "always on" scheduling gives the poorest performance in energy saving. However, it gives the highest sensing quality. This category is used mainly for comparison and evaluation purposes. In "random on-off" scheduling, sensor nodes are set active with a probability p. The probability p controls the averaged number of active sensor nodes in the network. The randomized effect in "random on-off" scheduling makes it capable in detecting random targets with short delays. However, the randomized effect also affects the performance in continuous tracking. In "selective on-off" scheduling, the sensing field is usually divided into grids. Only a limited number of nodes are allowed to stay active in a grid. An active node will remain active until its residual energy is fully depleted. By keeping a portion of nodes in active mode, "selective on-off" scheduling can provide short detection delay and high tracking quality. However, it also increases energy consumption required for the surplus sensing power, especially when system is sensing for rare targets. The performance of "selective on-off" scheduling is heavily dependent on the grid size. For large grid size, a grid may not be 100% covered by active sensor nodes. When the grid size is too small that the number of grids goes beyond the number of sensor nodes, empty grids will exist. Moreover, a battery with continuous discharge profile will have a shorter lifetime than that with pulsed discharge profile [2]. To obtain the maximum efficiency of "periodic on-off" scheduling, a network has to employ a centralized control method to acquire a global optimum sleeping schedule for each sensor node. Since centralized control increases system's overhead, the overall energy consumption increases with the network scale.

In this paper, a bio-inspired scheduling scheme is proposed. The proposed scheme is a kind of adaptive "selective on-off" scheduling scheme which uses only local information for making scheduling decisions. The objective of this paper is mainly on designing a scheduling scheme for detecting rare targets. The rest of the paper is organized as follows. Section II reviews the biological phenomena that inspire this work. Section III explains our proposed scheme. Three performance indicators are introduced in Section IV. Our proposed scheme will be evaluated against other generic scheduling schemes in Section V. Finally, Section VI and VII gives the related work and conclusions.

II. Biological Phenomena

In ant colonies, individuals are assigned to different task groups to perform different tasks such as foraging, patrolling and midden work. Biologists have found that the allocation of individuals among different tasks in ant colonies basically involves two mechanisms, namely the interactions among individuals from the same or different task groups and the task performance evaluations of individuals [3].

In ant colonies, the probability for an ant to carry out task A rather than task B depends on the ratio of the number of task A workers it has encountered recently to that of task B workers [4]. For an ant doing task A, a high encounter rate with other ants doing the same task will increase the probability for the ant to switch task. It is a kind of feedback system for controlling the size of different task groups which makes ant colonies adaptive to environmental changes.

When food sites start to deplete, more foragers return to their nest without food. When they are examined by the others, they are regarded as un-successful foragers. Encountering with un-successful foragers will stop non-foraging workers from switching to foragers [5]. Unsuccessful foragers will become inactive and idle in the nest. This mechanism forms a negative feedback in controlling an over-sized task group. A task group should shrink when its consumption outruns its contribution to the colonies.

III. Bio-Inspired Scheduling Scheme

The whole sensor network is analogous to an ant colony with each sensor node mimicking an ant. Different tasks in an ant colony are mapped to different operating modes of sensor nodes. The interactions among ants are represented by the information exchange among sensor nodes. Sensor nodes will make scheduling decision by examining information obtained from their neighbors. Our proposed scheme tries to coordinate the operation of each sensor node by using this local information.

For a network with N sensors, each sensor node is located in the sensing field with coordinates (x_i, y_i), where $i = 1...k...N$. Sensor nodes can be in either sleep mode, sniff mode or active mode, as shown in Fig. 1. The scheme runs in rounds, and each round lasts for time T. Sensor nodes are only allowed to switch mode at the end of each round. Each mode will have different levels of energy consumption, as described in the following:

- In sleep mode, sensor nodes are turned off completely.
- In active mode, sensor nodes will do sensing and exchange evaluation results with other active nodes. They will be switched off when they go to sleep mode.
- Sensor nodes in sniff mode will preserve energy by switching off their sensing components. However, their communication components will remain active to eavesdrop communications nearby. They will be switched off completely when they go to sleep mode.

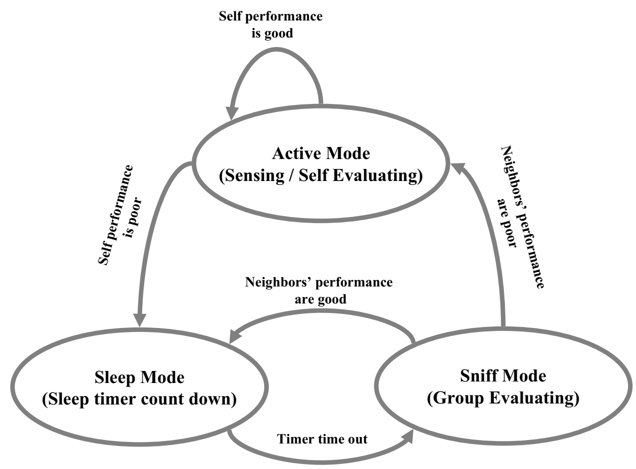

Fig. 1. State diagram of the bio-inspired scheduling scheme.

Thus, the energy consumption in active mode is the highest, followed by sniff mode, and the energy consumption in sleep mode is the lowest.

To initialize the scheme, all sensor nodes will be put into sleep mode for a random sleep duration t_s bounded by the system maximum sleep time $t_{s\_\max} = qT$, where q is a positive integer. A timer will be used for the count down of the sleep duration. The timeout of the timer will put sensor nodes from sleep mode back to sniff mode.

Sensor nodes in active mode will exchange their evaluation results with other active neighbors nearby. Sensor nodes in sniff mode will listen to the communication channel for time t_l, where $t_l \leq T$. By listening to the communication channel, sensor nodes in sniff mode can collect evaluation results of their active neighbors. An evaluation result can indicate whether an active node can detect a target (successful) or not (unsuccessful). The mechanism behinds it will be explained later. Any sensor node in sniff mode will use the evaluation results collected to give an evaluation function $E(n_{\text{sa}})$ which is given by

$$E(n_{\text{sa}}) = k_1^{n_{\text{sa}}} \tag{1}$$

where n_{sa} is the number of successful active neighbors and k_1 is a constant between 0 and 1. Sensor nodes in sniff mode will then generate a random number r_1, where $r_1 \in [0, 1]$, and compare it with $E(n_{\text{sa}})$. If r_1 is smaller than $E(n_{\text{sa}})$, the sensor node will become active in the next round. Otherwise, the sensor node will switch back to sleep mode. The sleep duration t_s, proportional to the complement of $E(n_{\text{sa}})$, is given by

$$t_s = \text{ceil}((1 - E(n_{\text{sa}})) \times t_{\text{s\_max}}). \tag{2}$$

Thus, a sensor will have a longer sleep duration if the performance of the neighbors is better, and vice versa.

In active mode, an active sensor node j will sense the surrounding environment for time t_{sen}, where $t_{\text{sen}} \leq \frac{T}{2}$. If an interested target is successfully captured within time t_{sen}, sensor node j will mark its evaluation result e_j as 1 (successful). Otherwise, the evaluation result will be reduced to 0 (unsuccessful). Upon obtaining its own evaluation result, sensor node j will broadcast its evaluation result towards its surrounding for time t_{bcast}, where $t_{\mathrm{sen}} + t_{\mathrm{bcast}} \leq T$. By the end of the round, an unsuccessful sensor node will switch to sleep mode, while a successful sensor node will remain active for another round. Nodes switch from active mode to sleep mode will sleep for a random duration which is again bounded by the system's maximum sleep time $t_{\mathrm{s\_max}}$.

IV. Performance Indicators

For ease of comparison, three performance indicators are defined. Their definitions are as follows.

1) Target 3-Coverage Hit-rate: Target hit-rate is the ratio of the total time a target is being detected to the total time a target is active inside the sensing field. A target is having N-coverage when it is covered by N active sensor nodes simultaneously. To obtain the location of a target in a two-dimensional plane, 3-coverage is necessary. Target 3-coverage hit rate is defined as the ratio of the total time a target is having 3-coverage to the total time a target is active inside the sensing field.

2) Averaged Detection Delay: Detection delay is a measure of the time delay from the time a target emerged to the time when it is first being detected. A system with small averaged detection delay can provide newly emerged targets' location information more rapidly and hence can facilitate the allocation of resources to their surroundings. We define the averaged detection delay in this paper as the time when a target emerged up to the time when it is first being detected by at least three sensor nodes at the same time.

3) Energy Consumption Per Successful Target Detection: Energy consumption per successful detection can reflect the power efficiency of the system. In this paper, successful detection refers to a target being captured by at least three sensor nodes simultaneously. Resources under-utilizing, resources over-utilizing and communication overhead will all increase the energy consumption per successful detection.

A. Simulation Settings

Simulations are carried out using MATLAB. In each simulation, a sensor network consisting of either 100, 300 or 500 sensor nodes will be distributed randomly in a sensing field of 50×50 m^2. Each sensor node will have a fixed sensing radius r_{sen} and a fixed inter-communication radius r_{com}. Although the inter-communication radius is usually larger than the sensing radius, broadcasting inter-communication packet to a large area will cause over-communication and degrade the performance of the scheme. Therefore, inter-communication radius r_{com} is set equal to the the sensing radius r_{sen}.

Each inter-communication packet will have a size of 25 bytes. By using a simple first order radio model [6], the energy consumption for broadcasting this inter-communication packet for r_{com} m will be $1 \times 10^{-5} + 2 \times 10^{-8} r_{\mathrm{com}}^2$ J. The energy dissipated in receiving this packet will then be 1×10^{-5} J. The energy dissipated in capturing one bit of data from the target is approximately equal to the energy dissipated in receiving one bit of data from a neighbor node [7]. Assuming that the target data is 10 times larger than the inter-communication packet (i.e., 250 bytes), the energy dissipated in capturing a target is approximately 1×10^{-4} J per target per round.

Initially, each sensor node is given 5 J of energy. When the residual energy drops below 0 J, the node is regarded as depleted and non-functioning. Networks under test are assumed to be synchronized by some kinds of synchronization mechanism such as the one described in [8] which is beyond the scope of this paper. While doing inter-communication, sensor nodes are assumed to employ multiple access scheme such as CSMA/CA. Since our focus here is the design of the scheduling scheme that can provide a sufficient number of sensor nodes, data collection processes such as routing [9][10][11], clusters formation [12][13][14] and data aggregation [15][16][17] are not considered in this paper. Nonetheless, with the sufficient number of active sensors, all these data collection processes can be built on top of the proposed scheduling scheme.

The moving target is a kind of point source phenomenon with an effective radius of r_{eff} m. The target is moving at a constant velocity of s m/round horizontally across the sensing field. An active target can be detected if the distance between the centroid of the target and that of an active sensor is within $r_{\mathrm{eff}} + r_{\mathrm{sen}}$ m.

Each simulation will take 10000 rounds. For different network size, 100 simulations will be used to obtain averaged values of (1) target 3-coverage hit-rate, (2) averaged detection delay, and (3) energy consumption per successful target detection.

V. Performance Evaluations

A generic "random on-off" scheduling scheme and a generic "selective on-off" scheduling scheme [1] are evaluated together with the proposed scheduling scheme for comparison purposes.

In the "random on-off" scheduling, each sensor node will generate a random number at the beginning of each round. A node will be active in the current round if its random number is smaller than the global active probability p, where p is a random number between 0 and 1. Otherwise, the sensor node will return to sleep mode until the end of the current round. Therefore, parameter p controls the total number of active sensor nodes in a network. To ensure there are sufficient number of active nodes to cover the whole sensing area, the active probability p is set inversely proportional to the number of nodes in the network and the sensing radius, i.e. $p = \frac{50^2}{\pi {r_{\mathrm{sen}}}^2} \times \frac{1}{N}$.

In the "selective on-off" scheduling, the whole sensing area will be divided into several grids. Only one sensor node in a grid will be set active. Once set, the selected node will remain active until its residual energy is depleted. The sensing field is divided into $y \times y$ grids where y is a function of r_{eff} and r_{sen}, i.e.,

$$y = \mathrm{ceil}\left(\frac{50\sqrt{2}}{2(r_{\mathrm{sen}} + r_{\mathrm{eff}})}\right). \tag{3}$$

In this case, the distance among active nodes in adjacent grids will be small enough to detect any target in between. Notice that in the "selective on-off" scheduling scheme, an

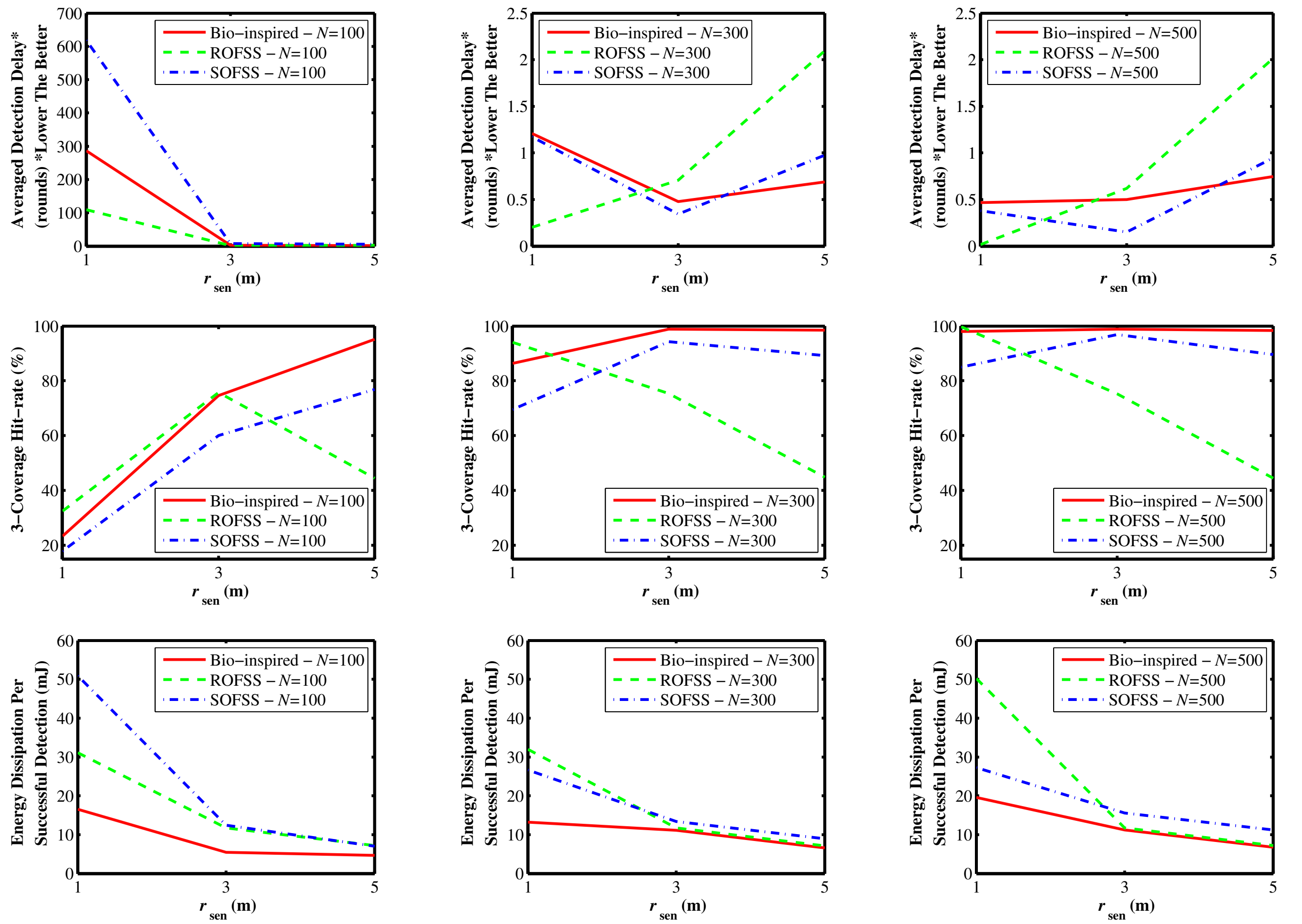

Fig. 2. Performance comparisons of the proposed bio-inspired scheduling scheme, the generic "random on-off" scheduling scheme (ROFSS) and the generic "selective on-off" scheduling scheme (SOFSS) with $s = 1$ /round, $r_{\text{eff}} = 3$ m.

active node has to communicate with all nodes within the same grid. Therefore, $r_{\text{com}} \geq 50\sqrt{2}/y$ m.

The objective of the proposed scheduling scheme is to minimize the energy dissipation while having insignificant impact to the sensing quality. Since the performance indicators are inter-contradicting, different priorities should be given to the three performance indicators in order to achieve the objective stated above. Minimizing the "energy consumption per successful target detection" is given with the highest priority, followed by maximizing the "target 3-coverage hit-rate". Minimizing the "averaged detection delay" is given the lowest priority. Simulation results are given in Fig 2.

Simulation results show that the proposed scheme can deliver an impressive performance in energy saving. When comparing with "random on-off" and "selective on-off" scheduling, the proposed scheme can reduce energy consumption up to a factor of 2/3. Such performance improvement is possible because the proposed scheme is able to *adaptively* perform selective on-off scheduling which only wakes up the necessary number of nodes while keeping most other nodes in sleep mode.

When the inter-communication radius is short and the node density is low, the 3-coverage hit-rate of the proposed scheme is slightly lower than the "random on-off" scheduling scheme. This can be appreciated as the short r_{com} and low N will isolate sensor nodes from each other and the proposed scheme will become a purely "random on-off" scheme. Since nodes in the proposed scheme have to sniff before going to active, the 3-coverage hit-rate of the proposed scheme is slightly lower than that of the "random on-off" scheme. When r_{com} and/or N increase, the nodes' sensing coverage areas increase. Thus, the 3-coverage hit-rate increases with r_{com}.

When the sensing radius is short and the node density is low, the proposed scheduling scheme is suffering from a high averaged detection delay. The averaged detection delay of the proposed scheme is greatly reduced when r_{sen} and/or N increase. Except for the case with extremely low sensing coverage, the averaged detection delay of the proposed scheme is comparable or even better to that of its counterparts. The differences is less than 0.5 round. Such impact is insignificant especially for rare targets with low velocity.

The proposed bio-inspired scheduling scheme is most suitable for energy aware systems where the node density is high, sensing radius is long and inter-communication radius is long.

VI. Related Work

Scheduling in sensor networks has been addressed by other researchers before. However, it should be noted that in the previous studies, the way scheduling is defined and the objectives can be different. For instance, Volker and Christoph's scheduling scheme [18] tries to route packet with the minimum time and energy. Their proposed scheme aims to distribute the transmission time slots dynamically among sensor nodes such that nodes with heavier loadings will have more time slots and avoid being the bottlenecks of the network. Barbara, Lance and Eric [19] proposed a scheduling scheme for data dissemination such that child nodes will be active only when they need to report to their parent nodes. Both schemes are focusing on energy saving in data collection processes while our proposed scheme is on reducing surplus sensing power adaptively.

Dan and Paul [20] applied ant colony optimization method on finding the optimum search path for sensor nodes to pass through several "areas of interest" in the sensing field. In their work, sensor nodes try to schedule the visiting order of these "areas of interest" such that their energy consumptions are minimized. Christian, Till, Eilian and Michael [21] noticed the resources competition among different sensing tasks on a single sensor node and developed a scheduler to tackle the problem. Their work is mainly focused on scheduling within a sensor but not scheduling from the network point of view. Target hit-rate and target coverage are not their main concern.

A more related piece of work is from Jean-Francois and Venugopal [22]. They investigated the relationship among sleeping duration, detection delay and energy consumption. Moreover, their work addresses a stationary sensing field while we try to track on a moving target in an adaptive way.

VII. Conclusions

A bio-inspired scheduling scheme is proposed. Simulation results show that when compared with other scheduling schemes for medium to large scale networks, the proposed scheme can reduce energy consumption up to a factor of 2/3 while maintaining the target 3-coverage hit-rates at the same level as the other generic schemes and with virtually no effect on the averaged detection delay. The proposed scheme is very suitable for rare target tracking in networks where the node density is high and energy saving is the crucial. For specific applications, the performance can be biased to either shorter detection delay or lower energy consumption by tuning the maximum sleep time and the suppressing parameter.

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