LEARNING AUTOMATA-BASED SOLUTIONS TO TARGET COVERAGE PROBLEM FOR DIRECTIONAL SENSOR NETWORKS WITH ADJUSTABLE SENSING RANGES

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"*Allah does not charge a soul except [with that within] its capacity*"
The Noble Qur'an, 2:286

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ABSTRACT

The extensive applications of directional sensor networks (DSNs) in a wide range of situations have attracted a great deal of attention. One significant problem linked with DSNs is target coverage, which primarily operate based on simultaneously observing a group of targets occurring in a set area, hence maximizing the network lifetime. As there are limitations to the directional sensors' sensing angle and energy resource, designing new techniques for effectively managing the energy consumption of the sensors is crucial. In this study, two problems were addressed. First, a new learning automata-based algorithm is proposed to solve the target coverage problem, in cases where sensors have multiple power levels (i.e., sensors have multiple sensing ranges), by selecting a subset of sensor directions that is able to monitor all the targets. In real applications, targets may have different coverage quality requirements, which leads to the second; the priority-based target coverage problem, which has not yet been investigated in the field of study. In this problem, two newly developed algorithms based on learning automata and greedy are proposed to select a subset of sensor directions in a way that different coverage quality requirements of all the targets could be satisfied. All of the proposed algorithms were assessed for their performances via a number of experiments. In addition, the effect of each algorithm on maximizing network lifetime was also investigated via a comparative study. All algorithms are successful in solving the problems; however, the learning automata-based algorithms are proven to be superior by up to 18% comparing with the greedy-based algorithms, when considering extending the network lifetime.

ABSTRAK

Rangkaian penderia berarah (DSNs) telah mendapat perhatian yang sangat luas disebabkan oleh aplikasinya yang menyeluruh dalam pelbagai keadaan. Salah satu masalah yang sangat ketara dalam DSNs adalah liputan sasaran, yang beroperasi berdasarkan kepada pengawasan sekumpulan sasaran secara serentak dalam kawasan tertentu, seterusnya memaksimumkan tempoh hayat rangkaiannya. Oleh kerana penderia berarah mempunyai sudut penderiaan dan sumber tenaga yang terhad, mereka bentuk teknik baharu untuk mengurus penggunaan tenaga secara berkesan adalah amat penting. Dalam kajian ini, dua masalah diajukan. Pertama, satu algoritma berasaskan *learning* automata baharu dicadangkan untuk menyelesaikan masalah liputan sasaran, dalam kes di mana penderia mempunyai tahap kuasa yang pelbagai (iaitu jarak deria yang pelbagai), dengan cara memilih satu subset arah-arah penderia yang boleh memantau semua sasaran. Dalam aplikasi yang sebenar, sasaran mungkin mempunyai nilai ketetapan liputan yang berbeza, yang mengarah kepada masalah kedua; liputan sasaran berasaskan keutamaan, yang masih belum diselidiki dalam bidang yang dikaji. Dalam masalah ini, dua algoritma yang baharu dibangunkan berasaskan *learning* automata dan *greedy* dicadangkan untuk memilih satu subset arah-arah penderia yang dapat memenuhi nilai ketetapan liputan yang berbeza bagi semua sasaran. Prestasi semua algoritma yang dicadangkan dinilai melalui beberapa ujikaji. Tambahan lagi, kesan setiap algoritma bagi memaksimumkan tempoh hayat rangkaian juga diselidiki melalui kajian perbandingan. Semua algoritma berjaya untuk menyelesaikan masalah tersebut; namun, algoritma berasaskan *learning* automata terbukti lebih cemerlang sehingga 18% berbanding dengan algoritma berasaskan *greedy*, apabila dibincangkan untuk memanjangkan tempoh hayat rangkaian.

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LIST OF ABBREVIATIONS

CCD	-	Charge-couple device.
CMOS	-	Complementary metal-oxide-semiconductor.
CP	-	Covering power.
CW	-	Covering waste.
DLA	-	Distributed learning automata.
DSN	-	Directional sensor network.
FoV	-	Field of view.
IR	-	Infrared.
LA	-	Learning automata.
MNLAR	-	Maximum Network Lifetime with Adjustable Ranges.
PIR	-	Passive infrared.
PTCASR	-	Priority-based Target Coverage with Adjustable Sensing Ranges.
RAM	-	Random-access memory.
RL	-	Residual lifetime.
TIS	-	Target in sector.
WSN	-	Wireless sensor network.

LIST OF SYMBOLS

α_i	-	The action set of automaton A_i.
Δt	-	The value of working time.
Δ^a	-	The ratio between battery consumption at level a and level 1.
a	-	Number of alternative power levels, $a \geq 1$.
A_i	-	Activated automaton.
C_{cur}	-	The new cover set or the cover set that is being formed.
C_i	-	The number of generated sets produced by the i-th generated topology.
D_{cur}	-	The set of directions of available sensors.
$d_{i,j}$	-	j-th direction of i-th sensor.
$(d_{i,j},\ a)$	-	Sensor direction $d_{i,j}$ activated at level a. This pair is also defined as adjusted sensor direction.
$g(t_m)$	-	The coverage quality required for target t_m; the value of $g(m)$ is selected between 0 and 1 randomly and uniformly.
k	-	The stage number, initially set to zero.
LF	-	Maximum network lifetime.
l_i	-	Lifetime of sensor s_i.
L_i	-	The amount of residual lifetime for each sensor s_i.
m	-	Number of targets.
Max_CF	-	The amount of contribution of the selected sensor direction.
n	-	Number of sensors.
$P_{selected}$	-	The set of targets covered by the adjusted sensor direction $(d_{i,j},\ a)$.
S	-	Set of sensors, $\{s_1, ..., s_n\}$.
$Selected$	-	The adjusted sensor direction with greatest contrubution.

s_i	-	A sensor for all $i \in \{1, ..., n\}$.
SOL	-	The cover sets with their related activation times.
T	-	Set of targets, $\{t_1, ..., t_m\}$.
t_c	-	The critical target.
T_{cur}	-	The set of uncovered target.
$T_{(d_{i,j},\, a)}$	-	The targets covered by sensor direction $d_{i,j}$ when it is set at level a.
t_k	-	A target for all $k \in \{1, ..., m\}$.
T_k	-	The dynamic threshold at stage k.
$u(x)$	-	The coverage quality function where x shows the ratio of the distance between the sensor and target to the sensing range; $u(x) = 1 - x^2$.
w	-	Number of directions per sensor, $w \geq 1$.

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Wireless sensor nodes are electronic devices that are capable of gathering, storing, and processing environmental information, and they can communicate with other sensor nodes via the wireless communications. A wireless sensor network (WSN) consists of too many wireless sensor nodes distributed in a region of interest. These nodes are typically assumed to have a disk-like sensing range (Yick *et al.* 2008). In the real world, however, sensor nodes may be restricted in their sensing angle where they can sense only a sector of a disk. These sensors are identified as directional sensors (e.g., ultrasound, infrared, and video sensors) and the networks composed of them are labelled as directional sensor networks (DSNs) (Ai and Abouzeid, 2006). Sensor nodes are battery-powered with limited lifetime, which means that they are non-rechargeable or irreplaceable in remote and harsh environments. Because of this, the capability to extend the network lifetime is very important to sensor networks.

One foregrounding problem in the sensor networks is coverage that refers to collecting different data-types from the environment. Coverage problem can be sub-categorised into the area coverage and target coverage (Guvensan and Yavuz, 2011b). In the area coverage, the whole area of interest should be subjected to continuous monitoring. In the target coverage, only some crucial points (targets) in the area have to be monitored. There are three sub-problems under target coverage: simple target coverage, *k*-coverage, and priority-based target coverage. In simple coverage, each target is observed by at least one sensor node. Simple coverage is not very accurate when it comes to its monitoring operation. This drawback shifts the attentions towards *k*-coverage wherein each target is examined closely by at least *k* sensor nodes, leading to improved reliability and accuracy of the monitoring operation. However, in real applications, targets may have different coverage requirements, which cause the *k*-coverage to be inappropriate for such situations. This feature of *k*-coverage leads to priority-based target coverage problem, whereby each target is observed by different number of sensor nodes guided by its coverage requirement (priority). The coverage requirement is in reference to the minimum quality of monitoring that each target requires. The coverage requirement is represented by a value that can be set with regard to the state of the problem (Zorbas and Razafindralambo, 2013). Therefore, one of the most important challenges is to address the priority-based target coverage problem and, simultaneously stretch the network lifetime.

1.1 Problem Background

One major operation of the sensor networks is collating data in inhospitable or remote environments. Since accurate placement of sensors has to depend on the cost and/or risks considerations, under such environments, sensors are normally deployed randomly. To make up for the inaccuracy in such random deployment, more sensors than needed are distributed in the field. Such an over deployment causes DSNs to be more robust as some targets are monitored by multiple sensors redundantly. Instead of having a limitation in their angle of view, each sensor is given with a limited-lifetime battery that cannot be easily recharged or replaced in tough environments. Therefore, the use of power saving mechanisms for lengthening the network lifetime is highly significant to DSNs design. In general, these mechanisms can be divided into two techniques: (i) scheduling sensor nodes activity, and (ii) adjusting the sensing range of sensor nodes (Cardei *et al.* 2006).

The technique of scheduling sensor nodes activity manipulates the redundancy in sensor deployment, where it organizes sensors into a number of cover sets each of which can monitor all the targets. Additionally, it governs the amount of time each cover set can be activated. Afterwards, the cover sets are activated successively for a duration that has been determined earlier. When a cover set is active, the sensors belonging to other cover sets are in inactive mode to enable their energy to be conserved. This significantly enhances the network lifetime due to the fact that inactive sensors consume considerably less energy than the active ones, and if the battery of a sensor frequently rotates between active and inactive mode, it tends to last longer (Singh and Rossi, 2013).

To show the efficiency of scheduling technique, the example network illustrated in Figure 1.1 is considered, in which there are four directional sensors and three targets. Let $s_n (1 \leq n \leq 4)$ represent the set of directional sensors and $t_m (1 \leq m \leq 3)$ denotes the set of targets. The figure also highlights that each directional sensor has three directions and $d_{i,j} (1 \leq j \leq 3)$ indicates the directions of sensor s_i. In this example, a single power level is contemplated for each sensor. A target can be monitored when it is within both the sensing region and sensing range of at least one active sensor direction. For example, target t_3 is monitored by $d_{2,2}$ and $d_{4,3}$, simultaneously. The possible cover sets for all targets are $\{d_{1,3},\ d_{2,1}\}$, $\{d_{2,2},\ d_{4,3}\}$ and $\{d_{2,2},\ d_{3,1}\}$. A cover set is a subset of sensor directions that can monitor the whole targets. Let us say that the battery of each sensor keeps the sensor active for 1 unit of time (classical assumption). By contemplating on one of the abovementioned cover sets, e.g., $\{d_{1,3},\ d_{2,1}\}$ and activating it for the whole battery life of the sensor, all the targets can be monitored for 1 unit of time. Consequently, the network lifetime can no longer be extended because only s_3 and s_4 have residual lifetime and they are not able to monitor all the targets. On the other hand, by considering three cover sets (i.e., $\{d_{1,3},\ d_{2,1}\}$, $\{d_{2,2},\ d_{4,3}\}$ and $\{d_{2,2},\ d_{3,1}\}$) and activating each of them for 0.5 units of time, the network lifetime would be equals 1.5 units of time. Conclusively, this strategy (i.e., scheduling technique) outperforms the previous one as it can extend the network lifetime.

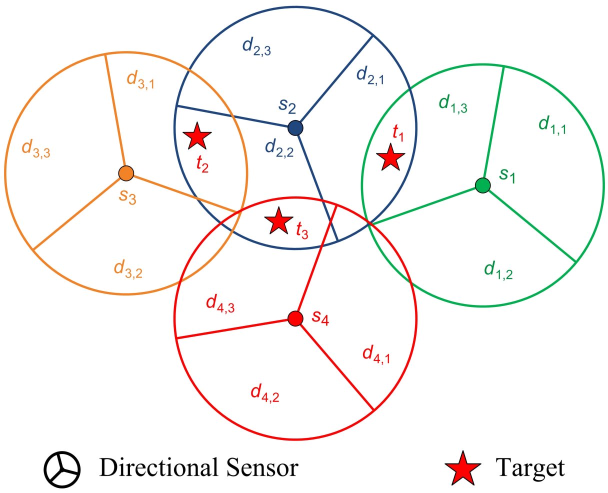

Figure 1.1: Example network with four directional sensors and three targets.

Another technique that can be used to extend the network lifetime is adjusting the sensing range of sensor nodes. This technique is used in the networks in which the sensors have various sensing ranges and helps a sensor save its energy whenever it is to monitor the targets in its vicinity. This is because the power requirement is a non-decreasing function of the distance between the sensor and the farthest target it monitors (Rossi *et al.*, 2012). The technique of adjusting sensing ranges (i.e., sensors have multiple power levels) can potentially increase the network lifetime. This is explained by the fact that it increases the number of feasible cover sets that may be included in the solution.

The efficiency of technique of adjusting sensing range is illustrated through the example network displayed in Figure 1.2 where there are four directional sensors, three targets, and two power levels. Figures 1.2(a) and 1.2(b) illustrate the sensing ranges of each directional sensor when set at level 1 and 2, respectively. In this study, $(d_{i,j},\ a)$ refers to sensor direction $d_{i,j}$ when activated at level a. The batteries are expected to be able to keep sensors active for 1 unit of time at power level 1 and 0.5 units at power level 2. If power level 1 is considered, there will be a single feasible cover set (i.e., $(d_{1,2},\ 1),(d_{2,1},\ 1),(d_{4,3},\ 1)$) and the total network lifetime equals 1. Meanwhile, by considering power level 2, there will be a wider set of cover sets and a network lifetime of 1.5 can be achieved (consider, for example, $\{(d_{1,3},\ 2),(d_{2,2},\ 2)\}$, $\{(d_{3,3},\ 2),(d_{4,1},\ 2)\}$, and $\{(d_{2,1},\ 2),(d_{4,3},\ 2)\}$ are activated for 0.5 units of time each). As a matter of fact, if the sensor directions and their sensing range are used in a suitable manner, the network lifetime can be considerably extended.

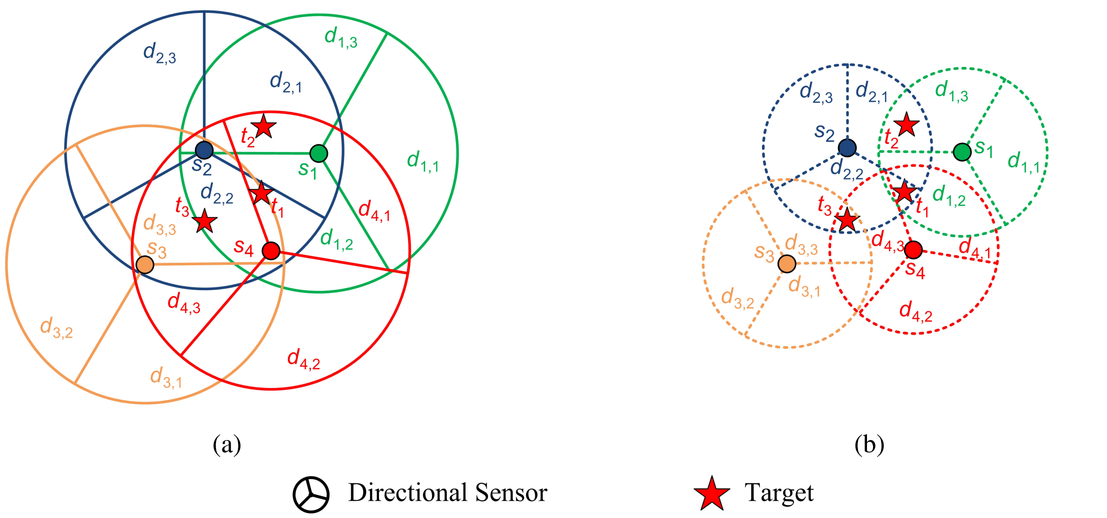

Figure 1.2: Example network with four directional sensors, three targets and two power levels.

1.2 Problem Statement

The problem addressed in this study is explained as follows:

One significant problem linked with directional sensor networks is target coverage, which primarily operate based on simultaneously observing a group of events (targets) occurring in a set area, and at the same time maximizing the network lifetime. Directional sensors cannot sense a circular region completely as there are limitations to its sensing angle. Additionally, they have limited energy resource and may cause difficulty in recharging the battery. In typical situations, it is assumed that sensors have a single power level. However, in some applications it may have multiple power levels that determine different sensing ranges and power consumptions. Due to these constraints, effectively managing the energy consumption of the sensors is highly important and the solution proposed for WSNs cannot be applied to DSNs. In real applications, each target may associated with a different priority reflecting its importance in the application and the quality of monitoring is depends on the distance between the directional sensors and targets. Thus, it is crucial to design a new technique to satisfy the coverage quality requirements of all targets, hence maximizing the network lifetime.

1.3 Objectives

The objectives of this research are outlined as follows:

(i) To provide a better energy efficient techniques with multiple power levels of sensors for solving the target coverage problem in DSNs.

(ii) To design a new heuristical algorithm for solving target coverage problem in DSNs with adjustable sensing ranges.

(iii) To develop new heuristical algorithms for solving the target coverage problem in DSNs with adjustable sensing ranges based on priority.

1.4 Research Questions

The general research question is:

How to organize sensor directions into several cover sets in such a way that each cover set can satisfy the different coverage quality requirements of all the targets and, simultaneously maximize the network lifetime?

Among the problems to be addressed are:

(i) How to adjust the working direction of each sensor using learning automata (LA)?

(ii) How to schedule the adjusted working direction using LA?

(iii) How to manage the critical targets in order to maximize the network lifetime?

(iv) How to select the efficient sensing nodes to satisfy the coverage quality requirements of all the targets?

1.5 Scope of the Research

Following are the scope covered in this study.

(i) The problem domain is lies on target coverage (i.e., *k*-coverage) and priority-based target coverage in directional sensor networks, in cases where sensors are assumed to have multiple power levels (i.e., adjustable sensing ranges), and each target is associated with a different priority reflecting its important in the application.

(ii) The solutions are based on heuristical approaches that aimed to extend the network lifetime (i.e., the amount of time during which the monitoring activity can be performed), where the simulation setup and the metrics for evaluating the solutions are based on the widely-accepted measures used in the problem domain. The heuristical method will be verified on simulations using MATLAB based on maximum 1000m^2 target coverage area and 500m^2 priority-based target coverage area.

(iii) All sensors are assumed to be homogeneous with respect to their angle of view and initial energy, and randomly deployed close to the targets with known locations, as to satisfy their coverage quality requirements.

1.6 Significance of the Research

This research introduces a solution to the target coverage problem in DSNs, where the sensors have multiple power levels (i.e. the sensing ranges are adjustable). The work can be significant because it recommends and develops several algorithms that can function as a benchmark for newly designed algorithms and it provides a criterion for other researchers to evaluate their algorithms with a near-optimal solution. Additionally, some efficient techniques are designed to manage the critical sensors; the issue not adequately covered in DSNs. These techniques can contribute to a longer lifetime of the total network. Considering both directional sensors and adjustable sensing ranges requirements together with managing the critical sensors, this thesis presents the target coverage problem more realisticly and practicably.

1.7 Organization of the Thesis

This thesis is organized into six chapters. Chapter 1 introduces the overall plan of this research. Chapter 2 reviews the literature related to scheduling sensor activities and lifetime maximization in DSNs, leading to the formulation of the research problem. Chapter 3 presents the research framework and methodology used in this research to achieve the research objectives and solve the research problems. Chapter 4 puts forth the setup of simulation environment in order to investigate the solutions. Chapter 5 demonstrates the obtained results with details discussion. Finally, Chapter 6 concludes the thesis and presents the limitations and contributions of the research and recommends issues that can be addressed in future studies.

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