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Algorithms of Wireless Ad Hoc Sensors in Robotics

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Abstract:

Algorithms of network sensors lifetime and target zones coverage, which are implemented on robotic wireless ad hoc nodes and wireless sensor network (WSN), are simulated on Matlab platform, with performance evaluations of several case studies. The main goal is to maximize the lifetimes of sensors by sharing sensors subsets which cover a number of targeted zones, according to their minimum coverage failure probabilities. Maximizing network lifetime due to perturbations in the sensor-target coverage, as well as due to variable target load demands is also simulated according to proposed algorithms.

1. Keywords

Ad Hoc; Algorithm; Failure probability; Lifetime; Robotics; WSN

2. Introduction

Sensor networks are normally deployed in areas of interest such as home appliances, healthcare applications, environment monitoring, as well as robotics, in order to collect information about events of these areas. Although using a large number of wireless low power ad hoc networks would be adequate, they are short lived, unreliable and limited radio range, memory and processing capacities **[1]**. An important function of these wireless sensor networks is to sense signals in remote and inaccessible environments, in which preserving their energy and prolonging network lifetime, is critical, and in which, their area coverage is to be maintained area coverage can be resolved either by deploying sensors to cover sensing zones completely, or make sure that all zones are covered by a certain number of sensors, such as one-coverage or k-coverage **[2,3]**, or select active sensors in a densely deployed network to cover all zones **[4-8**]. The last case is known as an Activity Scheduling Problem (ASP) **[9]**, which is divided into four classes: area, barrier, patrol or target coverage, in which this paper is focused on **[10].** In order to maximize network lifetime and preserving zones coverage, many algorithms propose to organize sensors in a number of subsets, such that each set completely covers all zones, thus enabling time schedules for each subset to be activated at a time, thus removing redundant sensors which may waste energy and consequently reduce network lifetime **[11]**. To solve this problem, many algorithms are applied such as generic, linear programming, greedy algorithms **[12-16].** One important technique is to improve reliability in cases when sensors may become unavailable due to physical damage, lack of power or malfunctioning.

In this paper, algorithms and their simulations of wireless sensor networks are implemented to include network lifetime reliability and lower failure probability of the sensor subsets which cover and monitor all zone targets. This problem has been addressed in the literature before; namely the α-Reliable Maximum Sensor Coverage (α-RMSC) problem. A number of algorithms, are introduced for a general S-T (sensor-target) coverage situation; each with a special task in a step-by-step simulation manner.

3.1. Algorithm of Network Sensors Lifetime and Target Zones Coverage

An S-T coverage problem is for S sensors covering T targets according to failure probabilities of a number of different subset groups of sensors, in which the target failure probability *tfp* of *j* targets by *r* sensors subsets ($r \in [1, k]$) are:

$$Cfp_r = 1 - \prod (1 - tfp_j) \quad (1)$$

$$tfp_j = \prod sfp_{ij} \quad (2)$$

Where sfp_{ij} is the failure probability of sensor *i* to target *j*, and cfp_r is coverage failure probability of a subset or group of sensors covering all targeted zones, which is assumed to be less than *α*; a predefined maximum failure probability *tfp* is target failure probability of one targeted zone by all sensors. It's required to find these *k* sensors subsets activation in order to maximize the network lifetime as

$$Max \sum (tw)_k \quad (3)$$

t_k and w_k are lifetime of each sensor subset and its effecting weight, with the assumption that lifetime of each sensor is normalized to a value of *1*. The aim is to increase this lifetime not on the expense of reducing the coverage.

A general sensor-target (S-T) case study model **[17]** is implemented initially in this study, in which three targeted zones are to be covered by four sensors, as depicted in **(Figure 1)**, with coverage pattern distributed randomly over a two dimensional planner view. Execution time required for solving these scenarios increases largely with the the model size, thought this has not been investigated in this study.

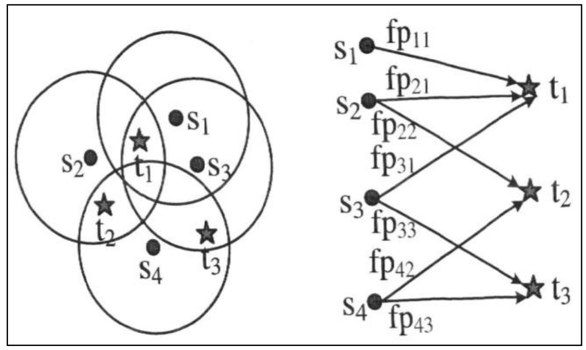

Figure 1: Planner view of four sensors and three target zones.

It can be seen that sensor S_1 covers target T_1 only, whereas S_2 covers T_1 and T_2, sensor S_3 covers T_1 and T_4, and sensor S_4 covers T_2 and T_3. It is assumed that two dimensional coverage pattern is assumed with the sensors allocated apart from the targeted zones' centers. Thus each sensor covers each target with a certain failure probability value (*sfp*), ranging from 0 to 1. A value of sensor failure probability of 1 indicates no coverage. Since each target is covered by one or more sensors, 100% coverage can be achieved in which alternative sensors alone or in groups, or subsets, can be switched on and off in such a way so that the lifetime of all sensors may be increased.

It can be seen that in order to insure 100% coverage of the targeted zones, there exists 9 possible sensor subsets or groups: {1,4}, {1,2,3}, {1,2,4}, {2,3}, {2,4}, {1,2,3,4}, {2,3,4}, {1,3,4} and {3,4}. Note that, a failure probability of one (1.0) in one of the targets; indicate no coverage to that target zone. So for the case of {1}, targets 2 and 3 are not covered, and for subset {1,3}, target 2 is not covered.

3.2. Lifetime versus Coverage Algorithm

The following flow chart depicts procedures and functions of the simulation program implemented on a Matlab platform **(Figure 2)**.

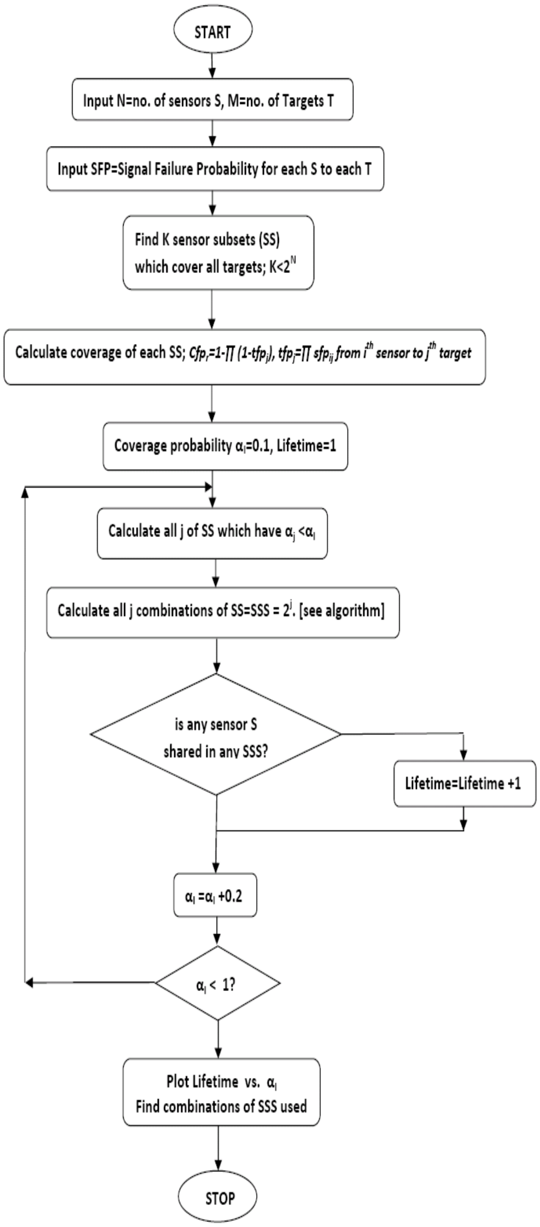

Figure 2: Flowchart of the simulation program.

This algorithm is to calculate network sensors lifetime for any required coverage for the target zones. That's to find the subsets of all sensors that cover all targets, in which one or more subset may contribute in covering all targets.

Firstly, the failure probability of all sensors *(i=1 to N)* to target *j (j=1 to M)*, is calculated according to $tfp_j=\prod\ sfp_{ij}$, where sfp_{ij} are sensor failure probabilities for a number of sensors to any target.

Next, a procedure is to calculate the coverage of the *k* sensors subsets to the *M* targets, as $scfp_r=1-\prod(1-tfp_j)$, in which $r \in [1, k]$; in which target failure probability *tfp* is entered as a vector for the *N* individual targets. All possible subsets covering all targets successfully, are compared with a required coverage, inputted by user, to find a new subset, as shown:

$$SSS=\{\{SS_1\}, \{SS_2\}\ldots\{SS_r\}\};\ r \in [1, k] \quad (4)$$

$$SS=\{S_1, S_2,\ldots\ldots S_k\}$$

As seen, there are maximum 2^k subsets of SS_r, in which some utilize one or more same sensors in S_k , thus the algorithm identifies this in order to find the combing SS_r sets which in effect can increase their sensors lifetimes.

In all simulations, different values of *α's* are chosen for sensor subsets, ranging from 0.1 to 0.9; the higher α value the more subset choices. It was seen from the above case study, that in order to maximize lifetime of sensors, it would be appropriate to activate many sensor subsets to operate at different times, thus elongating their lifetime. But this would be on the expense of coverage failure probabilities.

Then the weight factor indices *w's* are assigned to each sensor as well as to each target according to the importance of contributing sensors and targets to be covered. These weight indices are dependent on several factors, such as priority of targeted zones or sensors reliability, and therefore they will be included in the coverage lifetime of the contributed subsets. For evenly distribution of sensors and targets priorities, a value of unity is assigned to all *w's,* then, the maximum network lifetime is calculated according to the above-mentioned algorithm. The following simulations are implemented:

Full Sensor-target (S-T) network coverage of different S-T patterns with increasing number of targets from 3 to 6; i.e. 4S-3T, 4S-4T, 4S-5T and 4S-6T, as depicted in **(Figure 5)**. It's assumed here that a sensor failure probability *sfp =0.5* is used for all configurations **(Figure 3)**.

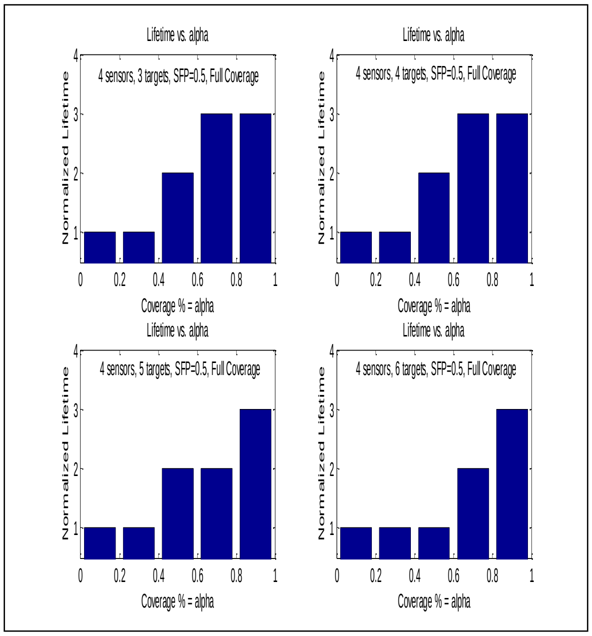

Figure 3: Network lifetime against required coverage failure probabilities for four sensors.

As seen, the coverage lifetime is reduced, as the number of targets increases. Maximum lifetime is 3 normalized times, which can be achieved even with reduced failure probability α from 0.9 to 0.7, and with α reduced down to 0.5, lifetime is doubled.

Next, sensor-target (S-T) network coverage of three sensors and two targets pattern, but with sensor failure probability *sfp* =0.2, 0.4, 0.6 and 0.8, as shown in Fig. 6, which shows that network coverage lifetime largely increases to 3 normalized time units, even with required coverage of *α=0.5*, as *sfp* decreases from 0.8 to 0.2. Further, the effect of the reduction of each sensor *sfp* is more dominant than the required value of *α* **(Figure 4)**.

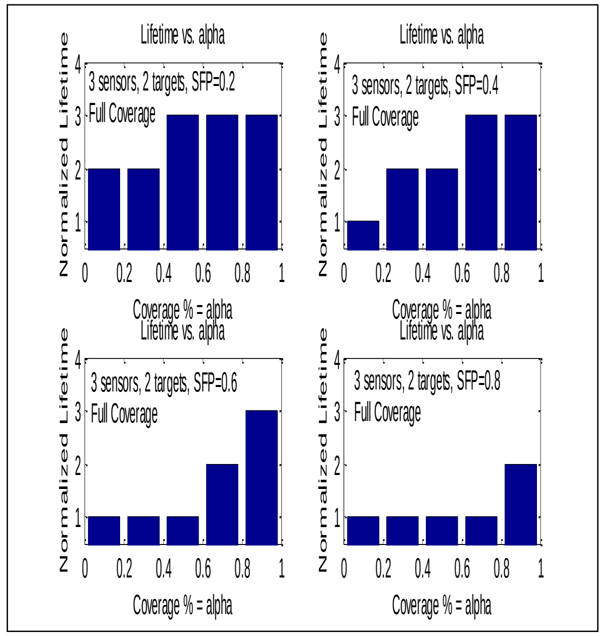

Figure 4: Lifetime of 3 sensors-2 targets with full coverages of different failure probabilities.

Different scenarios of a S4-3T pattern are simulated, such as; four sensors covering 3 target zones with different *sfp* as well with partial/full coverage of sensors, as depicted in **(Figure 7)**. It can be seen that a network lifetime of 4 can be achieved. The figure shows that full coverage between every sensor and target, is superior to partial coverage conditions with different *sfp* of 0.5 for all sensors, 0.1-0.9 or 0.9-0.1which have same lifetime vs. α patterns. It can thus be deduced, that full coverage is important measure for maximizing network lifetime **(Figure 5)**.

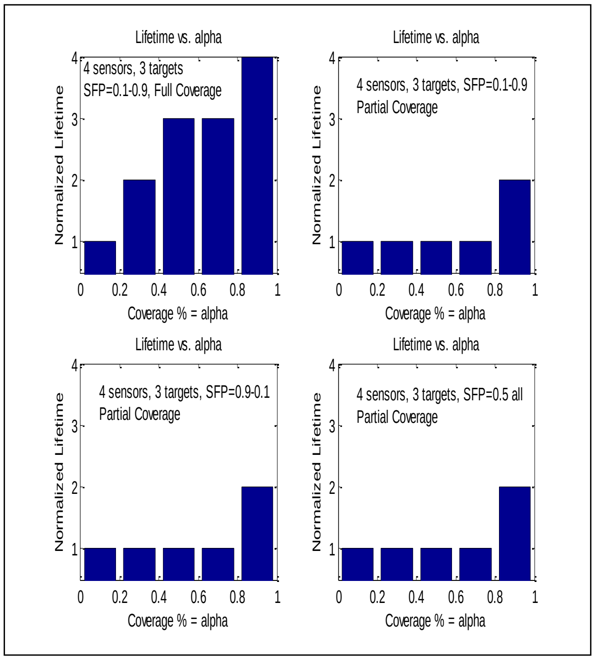

Figure 5: Four sensors-three targets simulations with random patterns of coverage parameters.

Next, a case of variable number of target zones, in which three sensors covering different numbers of targets ranging from 1 to 6; each with full coverage with *sfp=0.5* as an average value for this case. 3-D bar plot of lifetimes against required coverage failure probabilities ranging from 0.1 to 0.9, is depicted in Fig. 8. As expected, it can be seen, that with less number of target zones, lifetime is increased, and may reach to a maximum value of three normalized time periods, depending on the required network failure probability α.

The same results are depicted in a 2-D stem diagram of Fig. 6, in which both; the maximum and minimum values of sensor-target coverages are displayed, instead of network lifetimes. These maximum & minimum values correspond to the subsets utilized. The above-mentioned used algorithm calculates coverage value ranges for every subset found, which can cover the target zones with less than required failure probabilities **(Figure 6)**.

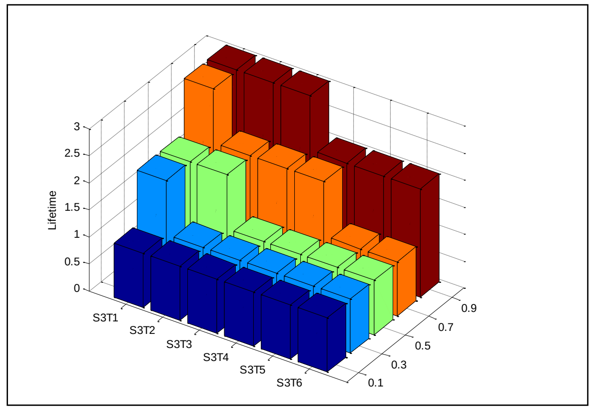

Figure 6: Lifetimes of three sensors with different number of targets and different coverage failure probabilities.

The maximum-minimum stem diagram of **(Figure 7)** below, can help in selecting the most appropriate combinations of covering subsets that have same lifetimes, and thus imposes priorities in choosing the right subsets.

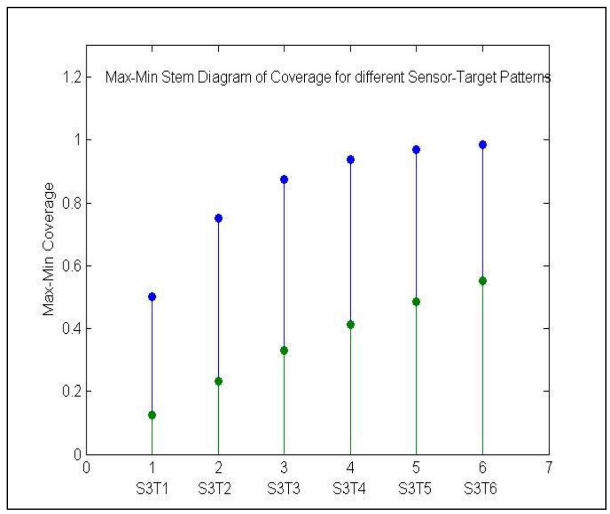

Figure 7: Maximum-minimum coverage values with different target zones by three sensors.

3.3. Algorithm for Variable Target Load Demands of Ad Hoc Networks

The coverage load in demand of the target zones is alternating or switching throughout the day, so it is necessary to distribute the n sensors to a couple of subsets in which each subset can cover the relevant targets in each time slot. Therefore, only one subset is active in a time slot of the duty cycle, in order to save overall energy and prolong WSN energy-lifetime.

There are different polynomials defining the target load demands over time period. These polynomials can be of different orders depending on the number of measuring points in any one period of time, as depicted in the following **(Figure 8)**.

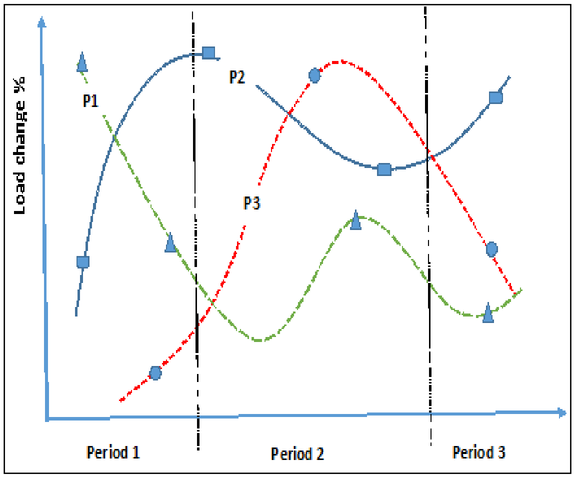

Figure 8: Target load polynomials.

(Figure 8) exhibits a case study in which three time periods are considered for the three target zones load demands, whereas each target requires a different load demand, as shown. A maximum 100% load is the default WSN design reference, so that energy can be preserved when the target load is below this reference, and might reach infinity when there was no demand, i.e. energy is saved for future demand. Note that any number of measuring points per period can be taken in principle, but we shall consider one measuring point per period here. The polynomial orders can be of any size for the different targets.

It is assumed that the transmitted and received power are related according to the following free space model

$$P_r(d)=P_t\,G_r\,G_t\,\lambda^2 / \{(4\pi)^2\, d^2\, L\} \qquad (5)$$

And for the non-free space

$$P_r(d)=P_t\,G_r\,G_t\,h_r^2\, h_t^2 / d^4 \qquad (6)$$

Where G_r and G_t are equal to $4\pi\, A_e /\lambda_2$ for receiver and transmitter, A_e is the effective antenna distance aperture, λ is wavelength, L is a lost factor, d is covered distance and P_t is transmitted power. And h_r and h_t are receiver and transmitter heights. It can be deduced that sensor power and energy are linearly proportional with the switching target load in demand, and thus on sensors energy.

The target load demand polynomial degree r can be of any order depending on measuring points p, in which $n<p$. **(Figure 4)** shows that different polynomial degree 0th, 1st, 2nd, 3rd can be generated from the shown 4 measuring points **(Figure 9)**.

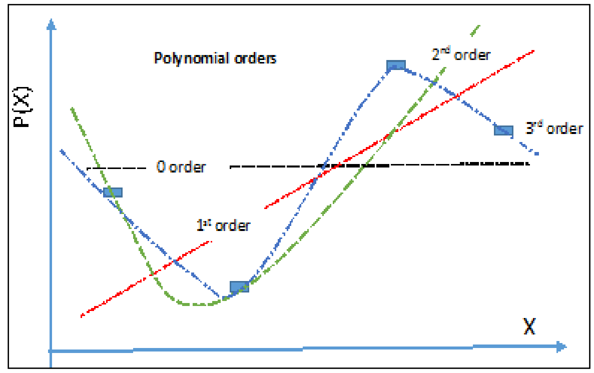

Figure 9: Polynomial degree order with 4 measuring points

Three considerations are taken into account for the above algorithm:

1- The required overall network failure coverage probability α is adjusted as

$$\alpha_{new}= \alpha_{old} + (1- max(L_i(j))) \qquad (7)$$

Where Li(j) is for all ith targets in the jth interval t. If this value exceeds unity, then it is equated to 1. This would increase the number of possible sensor subsets and therefore a possible lifetime increase.

2-The individual target failure probabilities of the j targets are increased by their load demands Li(j) as specified in time period intervals as

$$tfp_{i,\,new}= tfp_{i,\,old} +(1-L_i) \qquad (8)$$

Again, if this value exceeds unity, then it is equated to 1.

3-The total subset lifetime T_{totl} is calculated as

$$T_{total}= \sum T_j \qquad (9)$$

In which Tj is lifetime preserved or saved for period interval j, which is evaluated as:

$$T_j= i\; T_j / \sum L_i \qquad (10)$$

I.e. individual period lifetime is increased by $i/\sum L_i$ due to the fact that maximum default or reference energy is equal to the number of target time zones *i/t(j)*.

The total lifetime is computed by adding all lifetimes of the switching load periods, according to the area under the load demands, as depicted in equations 9-10.

The algorithm is tested on a general case study with target load demands, each having a polynomial of different degree, i.e. 1,2,3 and 4-degree. Up to 5 measuring load points are taken depending on polynomials. Also, 10 switching intervals are chosen, for the sensors over the period. The network lifetime is increased to 2.8574 times the lifetime when no switching is imposed. This is shown in **(Figure 10)**.

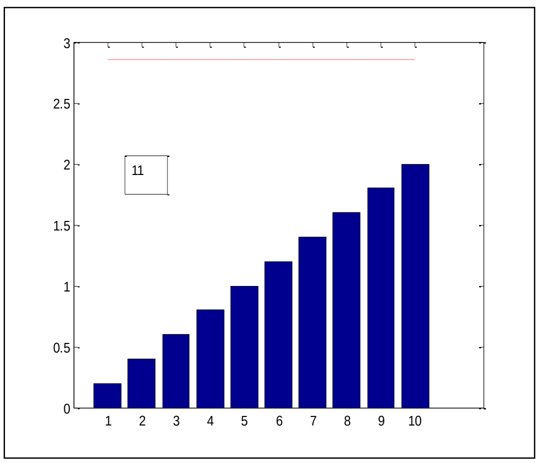

Figure 10: The general case study

It can be seen that at the end of each switching interval, a certain amount of lifetime, and consequently sensors energy and power, has been increased.

Varying polynomial for same target load measuring points, in which the load demand of case 3 is formulated as degree 2, 1 and 0. The lifetime is increased to approximately 3.5 depending on the individual target load profile. This is depicted in **(Figure 11)**

Figure 11: Lifetime versus load polynomial degree.

3.4. Maximizing Network Lifetime Due to Sensor-Target Coverage Perturbations

Consider perturbations in the sensor-target network, which leads to variations in the sensor failure probabilities. This will require adjusting sensors' positions accordingly in order to maximize and optimize network lifetime. This is depicted in **(Figure 12)**.

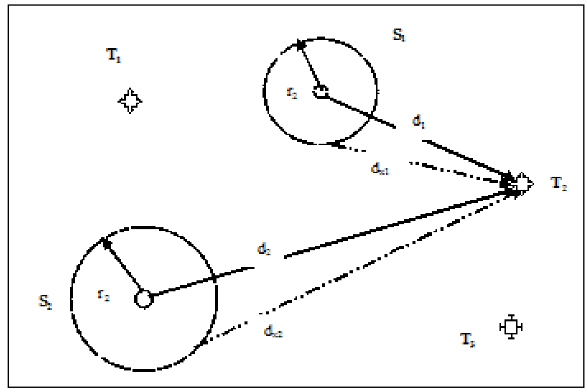

Figure 12: Perturbation in S-T network.

Any perturbations in the sensor-target network will be reflected in the values of signal failure probabilities in same proportions as shown in **(Figure 13)**. It is assumed that the sensor position can be varied in the polar variables r and x

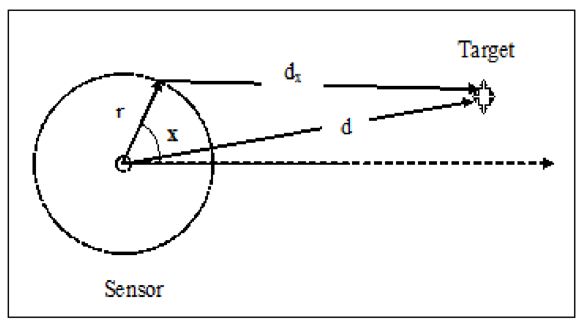

Figure 13: Perturbation geometry

It can be seen that the relation between d and d_x is

$$d_x =\{ [d \cos(y)-r \cos(x)]^2 + [d \sin(y)-r \sin(x)]^2\}^{0.} \quad (11)$$

Where y= $\tan^{-1}[(y_T - y_S)/(x_T - x_S)]$, and (x_S,y_S) and (x_T,y_T) are the sensor and target coordinates respectively.

Thus, the sensor failure probability sfp is corrected as:

$$Sfp_{new}=sfp_{old}\,(d_x/d) \quad (12)$$

It's required to find these k sensors subsets activation in order to maximize the network lifetime as

$$T = max \sum t_k w_k \quad (13)$$

Where t_k and w_k are lifetime of each sensor subset and its effecting weight, with the assumption that lifetime of each sensor is normalized to a value of 1. The aim is to increase this lifetime not on the expense of reducing the coverage. The following simulations are implemented:

- Full Sensor-target (S-T) network coverage of different S-T patterns with increasing number of targets from 3 to 6; i.e. 4S-3T, 4S-4T, 4S-5T and 4S-6T, as depicted in **(Figure 5)**. It's assumed here that a sensor failure probability *sfp =0.5* is used for all configurations **(Figure 14)**.

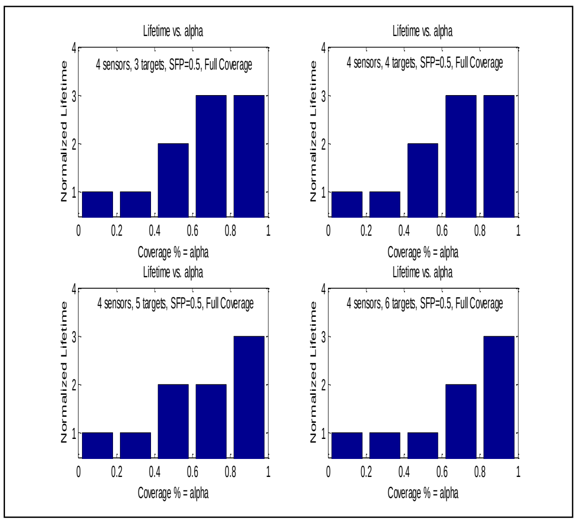

Figure 14: Network lifetime against required coverage failure probabilities for four sensors.

As seen, the coverage lifetime is reduced, as the number of targets increases. Maximum lifetime is 3 normalized times, which can be achieved even with reduced failure probability α from 0.9 to 0.7, and with α reduced down to 0.5, lifetime is doubled.

- Full Sensor-target (S-T) network coverage of three sensors and two targets pattern, but with sensor failure probability sfp =0.2, 0.4, 0.6 and 0.8, as shown in Fig. 6, which shows that network coverage lifetime largely increases to 3 normalized time units, even with required coverage of α=0.5, as sfp decreases from 0.8 to 0.2. Further, the effect of the reduction of each sensor sfp is more dominant than the required value of α **(Figure 15).**

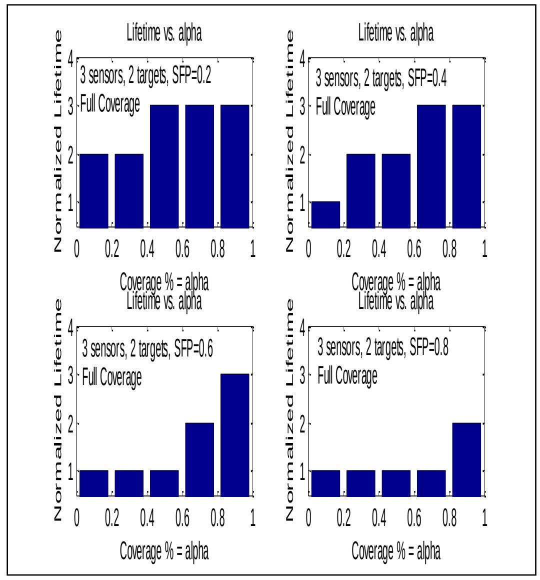

Figure 15: Lifetime of 3 sensors-2 targets network with full coverage of different failure probabilities.

- Different scenarios of a S4-3T pattern; i.e. four sensors covering 3 target zones with different *sfp* as well with partial/full coverage of sensors, as depicted in Fig. 7. It can be seen that a network lifetime of 4 can be achieved. The figure shows that full coverage between every sensor and target, is superior to partial coverage conditions with different *sfp* of 0.5 for all sensors, 0.1-0.9 or 0.9-0.1which have same lifetime vs. *α* patterns. It can thus be deduced, that full coverage is important measure for maximizing network lifetime **(Figure 16)**.

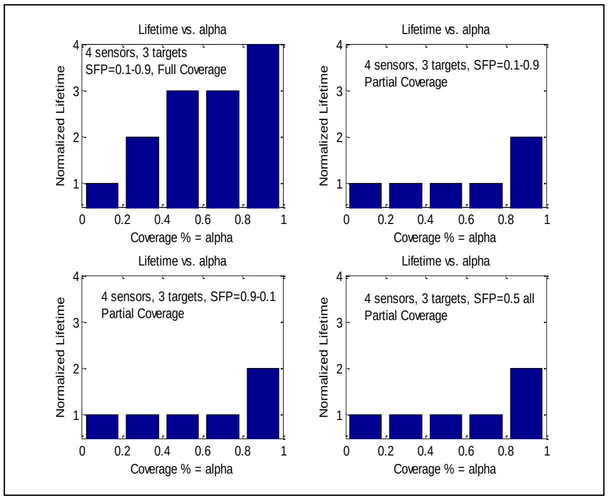

Figure 16: Four sensors-3 targets simulations of different and random scenarios of coverage parameters.

- Variable number of target zones, in which three sensors covering different numbers of targets ranging from 1 to 6; each with full coverage with sfp=0.5 as an average value for this case. 3-D bar plot of lifetimes against required coverage failure probabilities ranging from 0.1 to 0.9, is depicted in Fig. 8. As expected, it can be seen, that with less number of target zones, lifetime is increased, and may reach to a maximum value of three normalized time periods, depending on the required network failure probability α.

The same results are depicted in a 2-D stem diagram of **(Figure 9)**, in which both; the maximum and minimum values of sensor-target coverage's are displayed, instead of network lifetimes. These maximum & minimum values correspond to the subsets utilized. The above-mentioned used algorithm calculates coverage value ranges for every subset found, which can cover the target zones with less than required failure probabilities **(Figure 17)**.

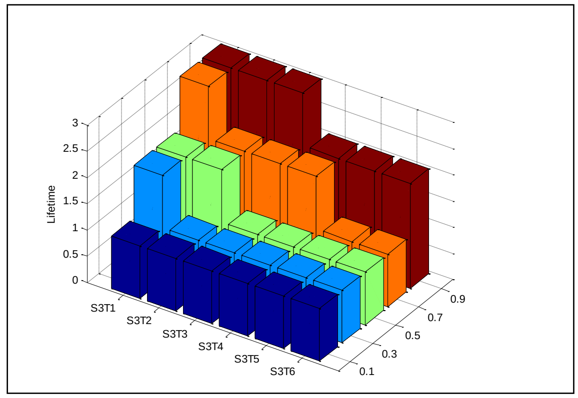

Figure 17: Lifetimes of three sensors with different number of targets and different coverage failure probabilities.

The maximum-minimum stem diagram of **(Figure 18)** below, can help in selecting the most appropriate combinations of covering subsets that have same lifetimes, and thus imposes priorities in choosing the right subsets **(Figure 18)**.

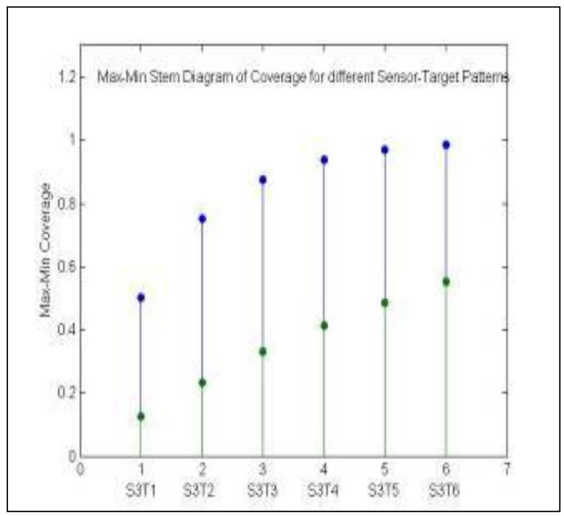

Figure 18: Maximum-minimum coverage values with different target zones by three sensors.

4. Conclusion

Algorithm of *wireless* sensors network in robotics, covering a number of target zones has been successfully implemented and simulated on Matlab platform. This algorithm is part of many procedures written in a script file to input sensor-target probabilities, calculate network coverage, selecting the covering subsets of sensors within specified required network failure probabilities, finding the combing subsets and their lifetimes. The major aim to maximize lifetime, which was displayed for a number of scenarios as a testing mean of the study algorithm. The algorithms can be applied on any number of sensors and target zones, as well as sensor-target failure probabilities ranging from 0.1 to 0.9 and in any manner. Execution time for this main algorithm increases largely with network size of more than 10 sensors and targets, which cannot be estimated. Such study was not conducted in this study.

A case study of 4 sensors targeting 3 zones has been used as a main platform, before updating, in step by step simulations for different values of failure probabilities. As expected, it has be seen that network lifetime can be increased with increasing sensors-targets coverages, reducing failure probabilities as well as reducing the demand for a certain required network coverage. Updating this case study to different scenarios of sensor-target patterns, shows that maximum lifetime can reach 4 when utilizing 4 sensors with full coverage of 3 targets. It can be deduced from simulations that lifetime can be increased with more sensors of full coverage to fewer target zones. The algorithm also calculates maximum to minimum ranges of coverages of the utilized combing subsets, and thus can be used for selecting the most appropriate subsets for maximum network lifetimes.

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