RANDOM VARIATION IN COVERAGE OF SENSOR NETWORKS

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ABSTRACT

Recently, Wireless Sensor networks become one of the most widely used form of ad-hoc networks that has a countless number of applications in our life. Due to the unreliable communication medium and the failure prone sensors, coverage is an important functional property of a sensor network. Coverage is represented as a function of sensor density, which in turn depends on sensing range and the deployment function. The sensing range and the deployment function have a random nature that can greatly affect sensor coverage. In our study, we subject a densely deployed sensor network to stochastic variations in sensing range and deployment. We capture deployment variations in space dimension by a random deployment pattern and a random noise. We also take into account time dependent random variation in noise and environmental factors. More specifically, we study the effect of randomness resulting in a certain percentage of uncovered area in the network.

KEYWORDS

Wireless Network, Coverage, Connectivity, Deployment, Node Density

1. INTRODUCTION

The recent advances in CMOS technologies and wireless communications have enabled the development of tiny, battery operated multifunctional sensor nodes [1]. These tiny devices are characterized by their low cost, short radio range, limited supply energy and inadequate processing capabilities. Providing unlimited number of applications, Wireless sensor networks (WSNs) are composed of a large set of sensors deployed randomly or uniformly in the field, where air is the communication medium between them. Typically sensor nodes have the ability of monitoring a wide variety of ambient conditions. Upon detecting an event, sensors cooperate together to deliver the sensed data to the base station (sink), thus each sensor acts as data source and data router for other sensors data. The applications in which sensor networks are valuable include surveillance, agricultural, medical, army, fire fighting and many more.

Sensor networks are subject to node failure due to severe power supply for sensor nodes. Thereby, coverage is by far the most important property of sensor networks that takes into account sensing ability of individual sensors in addition to the deployment strategy. Coverage problem is the problem of node deployment for the purpose of sensing [2]. In order to explain the importance of coverage problem consider a sensor network deployed for the purpose of intrusion detection. This sensor network must report every intrusion detected immediately in order to take the suitable action. At any time, if there is any part of the network that is not covered by sensor nodes undesirable consequences could happen. Therefore, we must guarantee the continuous coverage for the whole field.

Depending on the applications constraints Coverage problem can be studied as worst-case coverage [3], deterministic coverage [3], [4] or stochastic coverage [3], [4], [5], [6], [7].
Apart from sensing function, a sensor network also needs to attain the required connectivity in order to relay data to the appropriate nodes. Therefore, coverage and connectivity form the two basic topology/ density control properties of sensor network.

A region is fully covered if there is at least one sensor to cover every point in it. Extending this definition, a region is K-covered, if there are at least K sensors to cover every point in it. Coverage is also defined in terms of percentage of area covered. This is because; some applications may not require 100% coverage. In order to satisfy the coverage requirements aforementioned, the density of the deployed sensors along with the deployment strategy must be carefully studied
Apart from determining the sensor deployment density, there are other questions of vital importance. Most important of these questions, is energy efficiency and ensuring the connectivity property. Several protocols and algorithms exist to at the MAC, topology control and routing layers to attain these properties [13][14][18].
While connectivity takes into account transmission range of sensors, coverage deals with sensing range. However, there exists a relationship between the two properties given in (1) [5].

$$R_{sen\sin g} \geq 2 * R_{\tan smission} \qquad (1)$$

Coverage and sensor density also has deep implications for the design of MAC and routing protocols. Typically, in a dense system with stringent K-coverage requirement, high sensor density implies scalability and coordination problems.

The reminder of the paper is organized as follows: In the next sub-section we summarize the related work. In section 2, we shed light on the concepts of deployment density, sensing radius, sensor footprint and network lifetime. Section 3 presents the experimental results that support our model. Conclusion and directions for future work is discussed in section 5.

II. Previous Work

Coverage problem constitutes one of the fundamental problems in sensor networks; thereby a large work has been presented in this context. The sensor networks are energy constrained, there is preference for a small duty cycle in their sensing and transmission functions. The majority of the routing protocols focus on maintaining coverage (and thereby the connectivity) by conserving nodes energy during routing and also during sensing activities. For instance, PEAS protocol has proposed energy conservation mechanism for sensing functions via sleep cycles [14]. The protocol maintains working sensors while turning off unnecessary ones. The proposal assumes a dense network, so turning off some sensors will not affect the network performance. OGDC protocol, on the other hand geometrically optimizes coverage via minimum overlap [16].

In [8] the sensor network is partitioned into n non-intersecting cover set. Depending on the deployment, each cover set contains random number of sensors. Inside each cover set, any sensor can perform the sensing task, so it is possible to deactivate some sensors to save their energy if other sensors can perform the monitoring task. The monitoring task is rotated between the sensors so that their energy is consumed fairly.

A distributed coverage algorithm based on a node scheduling scheme is proposed in [9]. The algorithm uses directional antenna to gather geographical information regarding the sensor nodes (in addition to arrival of angle information). This information is used to determine which sensors should be activated (working set). GPS based sensor networks are characterized by high cost and high consumption of energy. High energy consumption may worsen the coverage problem in sensor networks. The work presented in [10] proved that the algorithm that is based on node scheduling has a low efficiency.

K. Kar, and S. Banerjee study the node placement strategy in order to attain connectivity in sensor networks [11]. The study involves sensing the field of interest with a minimum number sensor nodes but guaranteeing the connectivity between these nodes. In order to achieve the connectivity, the authors use deterministic node placement. In the study the authors assume the disk model for modeling the sensing area.

[12] demonstrates the possibility of improving the sensor network coverage by using multi-hop routing features. The paper also studies the effect of path length on the network performance and thereby network coverage. It optimizes the coverage constraint to the limited path length. Our study of coverage mainly focuses on random variation such as the uniform and the passion random node deployment on the percentage of the uncovered area.

Besides extending network lifetime via energy control, some researches include several other constraints in order to determine sensor density, Shakkottai et. al [17] have assumed a binomial probability of death of a sensor in an unreliable environment. They have analytically arrived at a critical value of sensor density in a unit-sensing disc that will ensure coverage. To the best of our knowledge, this work comes closest to ours. We, however, consider random variations in the sensor network to affect the sensor density.

In our work, we consider the effect of white noise and cumulative effect of other environmental factors, on the sensing range. To the best of our knowledge, no paper has yet considered the effect of noise and environmental factors on sensor density. The majority of the previous works (such as the ones mentioned above) focus on studying the influence of node deployment on the coverage and connectivity. We begin by considering the effect of stochastic variations along a one-dimensional sensing line and we plan to extend similar analysis to two-dimensional area in the subsequent paper. More specifically, we want to study the way in which sensor density would respond to stochastic factor in space and time. We also relate the notion of network lifetime to coverage and senor density.

2. SENSOR COVERAGE

In our study on sensor network coverage, we include the concepts of deployment density, sensing radius, sensor footprint and network lifetime.

2.1. Deployment Density

In our one-dimensional analysis, we assume deployment density to be the number of sensing elements per unit length of our sensing distance. We quantify our deployment density by parameter ‘A’, which is the distance between any two adjacent sensors along the sensing line.

Higher the deployment density, lower will be the value of A and vice versa. In fact, value of A depends on deployment density via an appropriate random density function.
The density function of deployment can be either deterministic or random in nature. In our study, we consider random placement of sensors along the sensing line. We perform our study for uniform and Poisson distribution of deployment density. The deployment density can be represented as uniform U(0,2A) and Poisson P(A) , using the parameter A.

2.2. Sensing Radius

Sensing radius corresponds to the distance dependent capacity of a sensor to perform its sensing function. For our study we assume, sensing radius of the sensor to consist of a deterministic constant and a stochastic variable. We further assume that the deterministic constant to be equal to the sensing range specified by the sensor manufacturers. We denote the manufacturer specified sensing radius as 'S'. The sensing radius also have a variable component in their sensing range, which may depend at any instant, on several external factors such as noise and environmental effects.
External noise on a sensor is a collection of several factors that result in an independent and identically distributed effect on sensing radius. Such an external white noise is assumed Gaussian with zero mean and unit variance. The effect of such noise is to increase or decrease the sensing radius, independently and individually for each senor in a random point in time. For instance, effect of noise on sensor s1 is independent of the same effect on sensor s2.
Likewise, effect of noise on a sensor at time t1 is independent of its effect at time t2. Thus, the effect of noise is to change the radius S, with a variance of S+1 or S-1 along the distribution N(S, 1).

2.3. Sensor Footprint

Footprint of a sensor is the relative area covered by a single sensor with respect to the net area covered by a network of sensors. Footprint of a sensor decides the strength of an individual sensor within a network of sensor. Sensor networks with a smaller footprint constitute a densely deployed system. In our study, we assume a small footprint of sensors mainly to study the effect of noise.

2.4. Network Lifetime

Lifetime of a network closely relates to the functions it has to perform. Typically, a sensor network performs coverage and connectivity. While coverage takes care of sensing function, connectivity relates to several other network related factors such as routing, energy conservation, topology control, medium access etc. In our case, we relate network lifetime to coverage and assume a strong relation between coverage and connectivity. Thus a network is alive and functioning well, if it attains the required coverage the applications demand. With such a perspective on network lifetime, we quantify the coverage dependent network lifetime in our case, by the percentage of uncovered area along the one-dimensional sensing line.
K-coverage is another level of complexity we impose on uncovered area and network lifetime. In case of a K-coverage situation, a certain percentage of networks need to attain K-coverage. K-coverage may be a redundancy requirement built into the application.

3. EXPERIMENTAL DESIGN

3.1. Average Percentage Uncovered

The main objective of this study is to quantify network lifetime in terms of percentage-uncovered length. Since, we need to relate percentage uncovered length to various parameter, we need to develop appropriate metrics and assumptions.

We assume a small footprint system with a fixed sensing capacity. The sensing capacity depends on the internal noise limited sensing radius as developed by the sensor manufacturers. In our experiment, we assume a sensing radius of 20 units. Our sensing line is 1000 units long.

Closely related to the sensing radius is the sensor deployment density. For the above-mentioned sensing radius of 20 units and sensing length of 1000 units and a deterministic placement, we have a sensor spacing of at least 40 units for coverage. However, due to stochastic placement, we may not be able to keep the spacing as 40 units between every pair of sensors. For instance, in case of uniform deployment U (0, 80) the spacing can vary from zero to 80 with equal chance. In order to compensate a spacing of say, 80 units, and assuming a constant sensing range of 40 units, we need to deploy more sensors to cover the entire area.

The number of sensors that needs to be deployed is further aggravated if we consider in addition to random spacing, the effects of noise and environment. The instantaneous sensing radius, which now depends of time and space varying noise and time varying environmental effects, will cause the uncovered length between sensors to change with time and space. Thus, at any instance in time, we have a certain value of uncovered length between any two adjacent sensors. We are interested in expected value of percentage-uncovered area because of the three effects considered above.

3.2. Parsimonious modelling

In order to model uncovered area as a function of random deployment (Uniform/Poisson), sensing radius, Noise and environmental effects, we introduce a variable ‘A’, the deployment spacing. We relate ‘A to sensing range, which is in turn related to fixed sensing radius ‘S’. For any sensor $S_i(t)$ (i = 1,2,3….N), with fixed sensing radius ‘S’, we have a stochastic sensing range si. The variation in sensing range is due to superposition of normally distributed noise and environmental effects on to the value of ‘S’. Thus at any point in time

Instantaneous sensing range of ith sensor: $S_i(t)$ = S + N(0,1) + N(0,V). Let X_i be the spacing between i-1th and ith sensors. Since we assume Uniform/Poisson distribution for sensor deployment with parameter ‘A’,

X_i = U(0, 2A) or X_i = Exponential(0,A).

In order to cover this sensor spacing completely by the two adjacent sensors,

For 1 coverage:

$$X_i = S_i - 1(t) + S_i(t) \qquad (2)$$

For 2 coverage:

$$2 * X_i = S_i - 1(t) + S_i(t) \qquad (3)$$

For K coverage in general:

$$2^{k-1} * X_i = S_i - 1(t) + S_i(t) \qquad (4)$$

The uncovered length between ith and i-1 sensors is given by:

$$U_i(t) = 2^{k-1} * X_i - S_i - 1(t) + S_i(t) \quad (5)$$

Since X_i depends on A, and $S_i(t)$ depends on 'S' for fixed value of 'V', A and S are dependent. Thus, we can fully characterize the system with a single variable 'A'. In addition, we control environmental and noise effects on our system by controlling our deployment parameter A. The random variation on the system is fully captured by a single variable 'A'. Thus in our study, we quantify network lifetime by the mean value of $U_i(t)$ which in turns relates to a system variable 'A'. Percentage of uncovered length = Expected [$U_i(t)$] / Total length.

4. RESULTS

In this section we present the experimental results in order to validate the Parsimonious modeling we proposed.

4.1. Studying the effect of random deployment and white noise

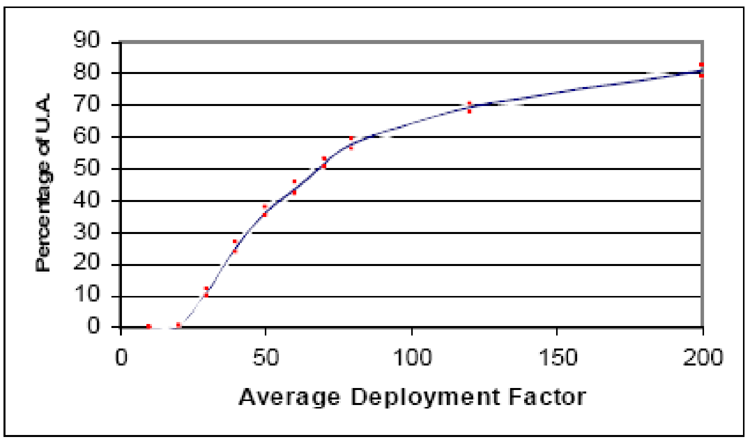

Figure 1. Percentage of uncovered length for uniform deployment (K=1, N(0,1))

Fig.1 shows the percentage of uncovered length (UA) for various values of deployment factor (A). Fig.1 assumes uniform distribution. The figure shows that the uncovered length increases as the average deployment factor increases. This is because a higher deployment factor (for a fixed value of sensing range) implies longer gaps between adjacent sensors thereby larger uncovered area. For smaller values of A, a random reduction in white noise compensates variations in deployment. This is because of N(0,1) representation of noise, where there is a chance for noise to take a negative value. Hence UA drops rapidly (almost linearly) for low values of A. For higher values of A, a larger decrease in A is needed to reduce UA. This is because, for higher values of A, compensating effect of noise is less powerful than what is seen at lower values of A. The same result is shown in Fig.2 but for passion distribution.

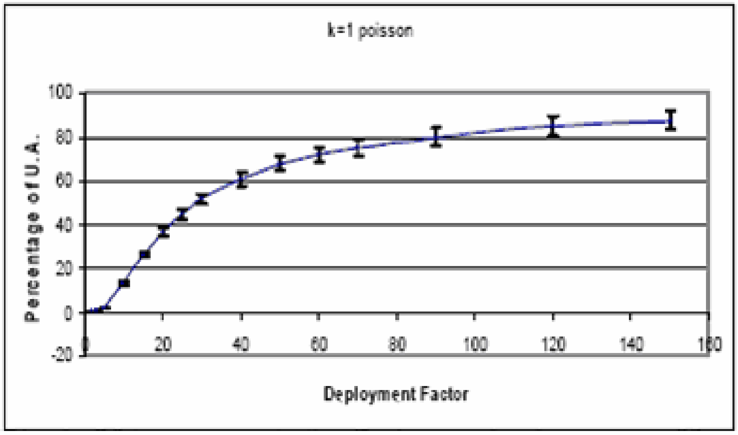

Figure 2. Percentage of uncovered length for passion deployment (K=1, N(0,1))

4.2. Studying the effect of K coverage

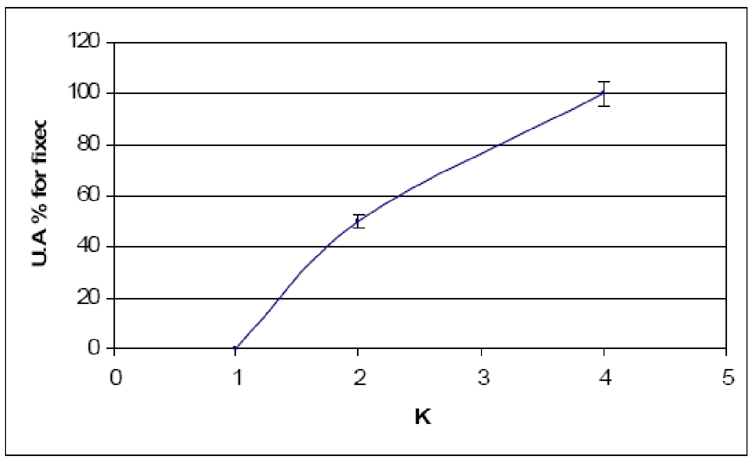

Figure 3. Percentage of uncovered length for different values of K

Fig.3 shows the percentage of uncovered area with respect of different values of K. It is obvious to note that the curves for K=2 and K=4 coverage are much steeper than the curve for K=1 coverage. This is because it is easier to violate the K coverage criteria for higher values of K. Thus, in order to provide K-coverage redundancy to applications, we may need very large deployment of sensors in the network.

4.3. Studying the environmental effects

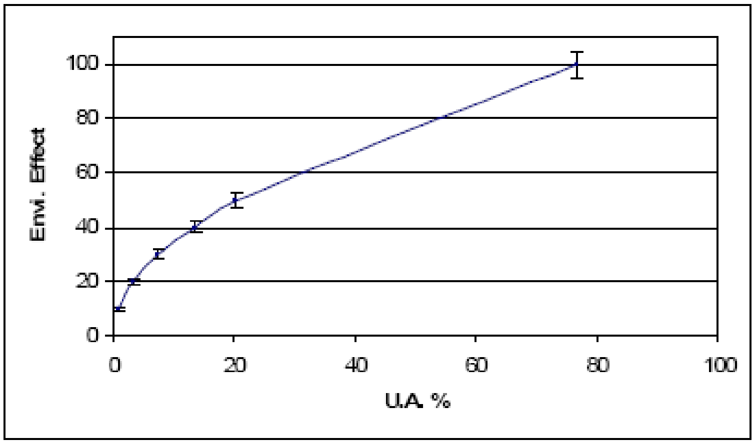

Figure 4. Environment effect versus UA for uniform distribution (A = 40 and K=1)

In contrast of noise, environmental effects affect all sensors equally. The environmental effect is given by (6). Fig.4 shows the relationship between the percentage of uncovered with respect to the environmental effects. As the environmental effects increase, the percentage of uncovered area increases. As discussed in the previous section, noise can have a negative excursion from its mean value. However, such a compensating effect does not exist for environmental effect.

$$Enviroment\ aleffects\ = V/A \tag{5}$$

This means further deterioration in values of UA as compared to pure white noise system. Generally, environmental effects also have a greater effect on stochastic variability than pure noise. This is apparent from high values of variance V for environmental effects. Fig.5 shows the effect of changing variance V on the percentage of uncovered area. The slope of the curve increases for large values of UA. Figure 6 shows percentage UA versus deployment factor A, taking into account, random uniform deployment, white noise and environmental effects.

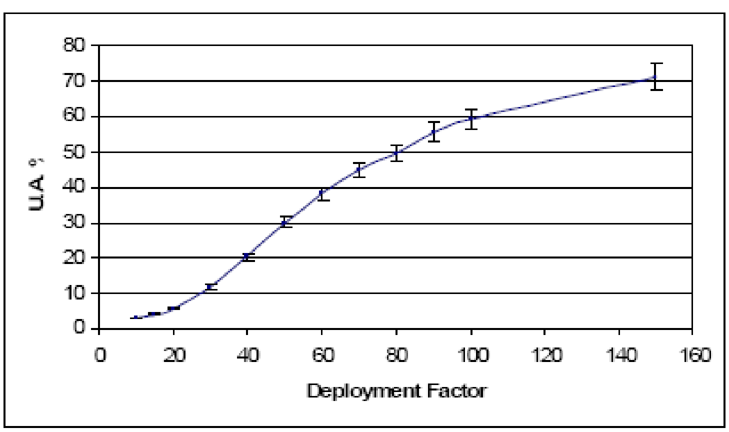

Figure 5. Percentage of uncovered with respect to deployment factor for uniform distribution V=20 and K=1

5. CONCLUSION AND FUTURE WORK

Results from our study on random variations in sensor network coverage, points to the fact that high degree of over engineering might be required for a system to attain homogenous coverage. The degree of over engineering is particularly crucial for small footprint networks, where the number of sensors per unit length is very high. High amount of sensors needed to achieve sensor network functionality such as coverage, has deep implications for design of MAC and routing protocol. Our future work will be to extend the analysis to coverage of a two dimensional area. We also plan to extend our analysis to the study of non-stationary, time dependent variation on the values of sensing coverage. As a future work, we are planning to study the network performance and connectivity for several deployment distribution techniques such as the Gaussian distribution.

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