Assuring *K*-Coverage in the Presence of Mobility in Wireless Sensor Networks

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***Abstract*— Along with energy conservation, it has been a critical issue to maintain a desired degree of coverage in wireless sensor networks (WSNs), especially in a mobile environment. By enhancing a variant of Random Waypoint (RWP) model [1], we propose Mobility Resilient Coverage Control (MRCC) to assure *K*-coverage in the presence of mobility. Our basic goals are 1) to elaborate the probability of breaking *K*-coverage with moving-in and moving-out probabilities, and 2) to issue wake-up calls to sleeping sensors to meet user requirement of *K*-coverage even in the presence of mobility. Furthermore, by separating the mobility behavior into average and individual, the probability of breaking *K*-coverage can be precisely calculated, hence reducing the number of sensors to be awakened. Our experiments with NS2 show that MRCC with the individual probability achieves better coverage by 1.4% with 22% fewer numbers of active sensors than that of existing Coverage Configuration Protocol (CCP) [2].**

I. INTRODUCTION

A wireless sensor network comprises numerous sensors, each with a limited computation, communication, and sensing capability in an unmanned mode. While energy efficiency in a WSN is a paramount issue because of the limited battery lifetime, a rigid assurance of K-coverage characterizes the monitoring quality provided by a WSN in a designated region; hence, addressing this problem is of utmost importance. Different applications, such as the intruder detection, guaranteed detection system in a multi-hop WSN, and distributed detection based on data fusion, require different degrees of sensing coverage [2, 3]. Mobility, which induces a fault in coverage and connectivity in a WSN, is one of the sources that makes solutions of the above problems harder [1, 4], and the same is true for Mobile Ad Hoc networks (MANETS) [5–7]. In considering mobility for WSNs, the biggest concern is maintaining a connected and covered network, while minimizing the power consumption so that the sensed data is safely delivered even in the event of breaking the confidence of coverage.

Certain topology control algorithms such as Span [8] and CCP [2] have been designed for assuring connectivity and coverage. Span adaptively elects coordinators from all the nodes in the network. Its goals are to ensure that sufficient coordinators are elected so that every node is in the radio range of at least one coordinator and to rotate the coordinators through the withdrawal mechanism in order to ensure that all nodes share the task of providing global connectivity. With the help of Span, CCP was devised to provide the specific coverage degree requested by an application with a decentralized protocol that only depends on local states of sensing neighbors.

In contrast to the above algorithms which consider stationary WSNs, we consider mobility in guaranteeing *K*-coverage. To properly model the mobility of objects, [9] suggested a scheme wherein mobile objects are uniformly distributed over a cell. Each chooses a direction θ and speed *v*, uniformly at random in intervals [0,2π) and [0,V_{max}], respectively. With optional operation of *thinking time*, an RWP model similar to [9] has been a commonly used synthetic model for mobility in Mobile Ad-hoc Networks (MANETS) [7, 10]. However this model fails to provide a steady state in that the average nodal speed consistently decreases over time, hence it is not pragmatic. Therefore [11] suggested a modified RWP model to be able to reach a steady state. For the coverage problem, [4] chose a direction $\theta \in [0,2\pi)$ and a speed $v \in [0,V_{max}]$ according to distribution density functions, $f_\theta(\theta)$ and $f_V(v)$, respectively. Its approach is that, when lacking in sensors, a sensor node can give better coverage by sweeping the field of interest. [1] used a mobility model for choosing a waypoint uniformly like RWP so as to build a robust connectivity topology, a Local Minimum Spanning Tree. Unlike [1], we consider the mobile sensor conditioned on the maximum possible area of movement, rather than sensing area, for coverage. In [12], the authors suggested several algorithms that identify and minimize existing coverage holes based on a Voronoi diagram and then computed the desired target positions where sensors capable of movement should move, while sensors in our scheme are not required to specify their destinations.

The rest of this paper is organized as follows: Section II introduces the basic concept and corollaries of *K*-coverage. In addition, we reformulate the average and individual probabilities in our mobility model. We will explain the experiments conducted with NS2 for our scheme in Section III. Finally the conclusion and future work are mentioned in Section IV.

II. MOBILITY MODEL AND MRCC PROTOCOL

As proposed in [2] the definition of K-coverage is that any point in a concerned field is covered by at least K sensors. Based on this definition we want to devise corollaries giving the surplus number of sensors to assure the degree of coverage by issuing wake-up calls to sleeping sensors.

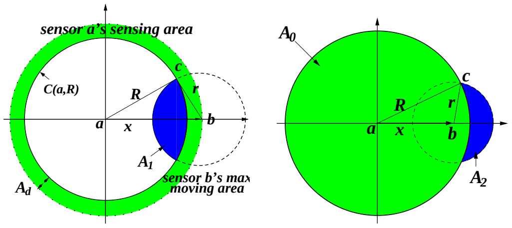
COROLLARY 1 *If a given topology of a WSN is assured by an optimal algorithm for K-coverage regardless of deployment distribution of a set of sensors, an active sensor node has to keep* ***at least*** *k-1 neighbors in its sensing range R_s.*

COROLLARY 2 *In a given topology assured by an optimal algorithm for K-coverage, when a sleeping sensor initiates its sensing activity within its sensing range, it should have* ***at least*** *k neighbors on already active duty.*

Based on the corollaries of necessary condition of *K*- coverage we plan to devise a mobility-resilient topology control for coverage with a modified RWP model for mobility in the following sections so that initiating some of sleeping sensors prevents frailty of K-coverage.

A. Probabilities in Mobility Model

Like RWP of [7], we consider four probabilities of sensors moving-in/out, in an average and individual way. Furthermore we reformulate the moving-in probability with the location area A_d of outside sensors which deemed to move in while [1] used A_0 in the conditional part. We compare the difference in calculating moving-in probability with [1] and derive the average and individual probabilities with the following assumptions of our mobility model; 1) All nodes are randomly distributed within a circle of area A_0 with sensing radius R and the total number of nodes N is known, 2) for a short time interval of length t, each node moves independently toward a random direction in $[0, 2\pi)$, with a constant speed v that is uniformly distributed in $[0, v_{max}]$ and it may stay still for a while, and 3) the locations of sensors are known using either GPS or trilateration.



(a) Moving in (b) Moving out

Fig. 1. Probability of Moving in vs. Moving out

Under these assumptions, within a range interval r which is a function of time t, two observations can be made which can model probabilistically 1) that a new neighbor sensor b moves into the detection range of node a in Fig. 1 (a) and 2) that an existing neighbor b moves out of the detection range $C(a, R)$ in Fig. 1 (b), $\overline{P}_{m.i}$ and $\overline{P}_{m.o}$, respectively. $C(a, R)$ is denoted as the circle of radius R centered at node a.

1) Probability of ***Moving in*** *$C(a, R)$, $\overline{P}_{m.i}$:* Suppose node a is located at point a with its neighbor b at point b as shown Fig. 1 (a). The maximum detection range of node a is R and the distance between node a and b is x where x is larger than R. Also let point c be an intersection of a circle made by point a with radius R and a circle made by maximum movement of point b with velocity v_{max} over time t. Then $\overline{bc}$ becomes $r = v_{max} \cdot t$ and the probability that node b moves into the detection range of node a within time t is the probability that node b moves into circle $C(a, R)$, which is exactly the shaded area between two circles as shown in Fig. 1 (a). This probability can be calculated in terms of the following two cases.

Case I: $0 < r < 2R$

$$\overline{P}_{m.i} = \int_{R}^{R+r} \frac{2\pi x}{A_d} \frac{A_1}{\pi r^2} dx = \int_{R}^{R+r} \frac{2A_1 x}{A_d r^2} dx, \qquad (1)$$

where $A_1 = \alpha_1 R^2 + \alpha_2 r^2 - xR \sin\alpha_1$, $A_d = \pi((R+r)^2 - R^2) = \pi(2rR + r^2)$, $\alpha_1 = \angle cab = \arccos\frac{x^2+R^2-r^2}{2xR}$, and $\alpha_2 = \angle cba = \arccos\frac{x^2+r^2-R^2}{2xr}$.

Case II: $r \geq 2R$

$$\begin{aligned}\overline{P}_{m.i}=&\int_{R}^{r-R}\frac{2\pi x}{A_d}\frac{\pi R^2}{\pi r^2}dx+\int_{r-R}^{r+R}\frac{2\pi x}{A_d}\frac{A_1}{\pi r^2}dx\\=&\int_{R}^{r-R}\frac{2\pi R^2 x}{A_d r^2}dx+\int_{r-R}^{r+R}\frac{2A_1 x}{A_d r^2}dx\\=&\frac{R^2(r-2R)}{r^2(r+2R)}+\int_{r-R}^{r+R}\frac{2A_1 x}{A_d r^2}dx.\end{aligned}\tag{2}$$

The first fraction in Eq. (1) explains the conditional probability about the existence of the sensor at point x and the second fraction is the ratio of area A_1 to total area of node b's movement. Unlike [1], in Eq. (1) and (2) we considered A_d as a conditional probability because the probability of location of outside sensors is represented by A_d, not A_0. The first term of Eq. (2) considers the case that the movement circle is larger than the sensing circle of sensor a so that the former circle includes the latter. The second term in Eq. (2) represents a situation where there is an intersection between movement circle and a sensing circle of sensor a.

*2) Probability of **M**oving **o**ut $C(a,R)$, $\overline{P}_{m.o}$:* The probability that one of neighbors inside circle $C(a,R)$ moves out of the detection range of node a within time t is the probability that node b moves out of circle $C(a,R)$, more specifically, which is the shadowed area outside of detection circle made by node a as shown in Fig. 1 (b). There are three cases depending on the interaction between sensing circle $C(a,R)$ of a given node and the range of the mobile node which can be enumerated as, 1) intersection, 2) eclipse, or 3) inclusion, which can be formulated in the following manner,

Case I: $0<r<R$

$$\overline{P}_{m.o}=\int_{0}^{R}\frac{2\pi x}{A_0}\frac{A_2}{\pi r^2}dx=\int_{R-r}^{R}\frac{2A_2 x}{A_0 r^2}dx,\tag{3}$$

where $A_2=(\pi-\alpha_2)r^2-\alpha_1 R^2+xR\sin\alpha_1$.

Case II: $R\leq r<2R$

$$\begin{aligned}\overline{P}_{m.o}=&\int_{0}^{r-R}\frac{2\pi x}{A_0}\frac{\pi(r^2-R^2)}{\pi r^2}dx+\int_{r-R}^{R}\frac{2\pi x}{A_0}\frac{A_2}{\pi r^2}dx\\=&\frac{\pi(R+r)}{A_0 r^2}(r-R)^3+\int_{r-R}^{R}\frac{2A_2 x}{A_0 r^2}dx.\end{aligned}\tag{4}$$

Case III: $r\geq 2R$

$$\overline{P}_{m.o}\;=\;\int_{0}^{R}\frac{2\pi x}{A_0}\frac{\pi(r^2-R^2)}{\pi r^2}dx=\frac{\pi(r^2-R^2)R^2}{A_0 r^2}.\tag{5}$$

In Eq. (4) the first term shows that the center of moving circle larger than $C(a,R)$ ranges from 0 to $r-R$ resulting in the moving circle encompasses the circle $C(a,R)$ while the second term accounts for the intersection between moving circle and circle $C(a,R)$.

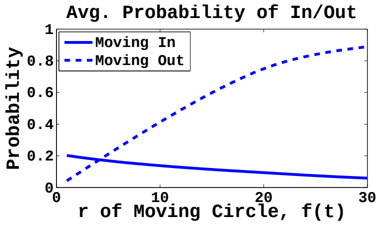
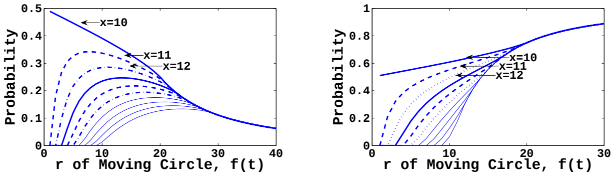


Fig. 2. $\overline{P}_{m.i}$ vs. $\overline{P}_{m.o}$



(a) Moving in (b) Moving out

Fig. 3. Probability of Moving In/Out according to distance of active sensor

Fig. 2 depicts the functions of $\overline{P}_{m.i}$ and $\overline{P}_{m.o}$ considering all equations from (1) to (5) according to r for $R_s=10$ whose value decides the stiffness of these functions, not the monotonic increase nor decrease. While $\overline{P}_{m.i}$ starts at 0.2 and decreases gradually, $\overline{P}_{m.o}$ increases expeditiously. Eq. (1) through Eq. (5) have been devised for average probability meaning that regardless of distance variable X from the area of interest, every sensor has the same probability. But intuitively at given same time t sensors at near outside rim or inside perimeter have larger probability of moving in or out, respectively. Therefore if we specify this individual probability of moving in and out, each sensor can make more accurate decision. This insight can be formalized in the following equations,

$$P_{m.i|X=x}=\begin{cases}\dfrac{A_1}{\pi r^2} & 0<r<2R, R\leq x<R+r\\ \dfrac{R^2}{r^2} & r\geq 2R, R\leq x<r-R\\ \dfrac{A_1}{\pi r^2} & r\geq 2R, r-R\leq x\leq r+R\end{cases}\tag{6}$$

and

$$P_{m.o|X=x}=\begin{cases}\dfrac{A_2}{\pi r^2} & 0<r<R, R-r\leq x<R\\ \dfrac{(r^2-R^2)}{r^2} & R\leq r<2R, 0\leq x<r-R\\ \dfrac{A_2}{\pi r^2} & R\leq r<2R, r-R\leq x\leq R\\ \dfrac{(r^2-R^2)}{r^2} & r\geq 2R, r-R\leq x\leq R.\end{cases}\tag{7}$$

Compared to Eq. (1) through Eq. (5), these questions are formulated by taking out the conditional probability, like $2\pi x/A_0$, of a sensor's location in average probabilities.

Fig. 3 shows these individual probabilities of $P_{m.i}$ and $P_{m.o}$ with $R=10$ according to r. Depending on the distance to a particular sleeping sensor, $P_{m.i}$ has peak value while $P_{m.o}$ has only gradual increase regardless of r. Compared to Fig. 2 plotting average probabilities, Fig. 3 shows the noticeable difference meaning that using individual probability in deciding coverage assurance in mobility is more accurate than average probabilities.

B. MRCC Protocol Mechanism

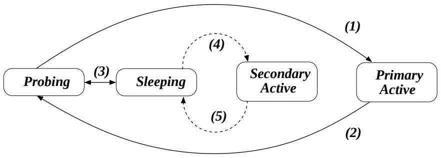


Fig. 4. Diagram of Status Transition in sensors for MRCC

Usually topology control mechanism operates between routing layer and MAC layer so that the routing layer uses information of rigid infrastructure of a WSN, built by the topology control algorithms [2, 8]. Besides these basic mechanisms of becoming active sensors, we need additional ruling of transition of sensor status from sleeping to active sensor.

As suggested in [2, 8], three solid lines with (1), (2) and (3) are the transitions of becoming *primary active* sensors to provide guaranteed coverage over whole field. *Probing* sensors which want to be *primary active* sensors need to be asychronized to figure out their roles, otherwise a group of sensors are blindly set to wake up to cover the same coverage hole at the same time. Once the roles of each sensor is decided, we need to choose some of *sleeping* sensors which have breaking probability calculated by Eq. (8) lower than predefined threshold value. Two dotted lines of (4) and (5) explain these situations where each of sleeping sensors asynchronously figure out the probabilities to become a *secondary* sensor.

After each sensor does a probing operation about deciding duty sensors for K-coverage by an optimal algorithm, as stated in *Corollary* 1 and 2 each sleeping sensor is required to be K-covered by the optimal algorithm and therefore from the point of each sleeping sensor it can observe the number of active **in**side sensors N_{in} in its radius R_s. We can determine the number of **out**side active sensors, N_{ot}, by probing the neighborhood of the given sensor, from R to $2R$ because sensor field connectivity requires $R_c \geq 2R_s$ to be satisfied where R_c is the communication radius [2]. Hence the distance between sensors can be measured based on transmission signal during K-coverage configuration.

Based on the equations, Eq. (1) through Eq. (5), depicting the average probabilities of sensors moving in/out, we can formulate the probability of breaking the K-coverage of a sleeping sensor, given N_{in} and N_{ot}. Suppose there are random variables $N_{m.o}$ and $N_{m.i}$ about the number of sensors **m**oving-**o**ut sensors from inside and sensors **m**oving-**i**n sensors from outside, respectively. Then the probability of breaking K-coverage $\overline{P}_B$ considering two random variables N_{in} and N_{ot} gives us two following cases, one of which is for $N_{in} = K$ and the other of which is for $N_{in} = K + \alpha$,

$$\overline{P}_B = \begin{cases} \displaystyle\sum_{l=1}^{N_{in}} P(N_{m.i} < l \mid N_{m.o} = l) P(N_{m.o} = l) \\ \displaystyle\sum_{l=\alpha+1}^{N_{in}} P(N_{m.i} < l - \alpha \mid N_{m.o} = l) P(N_{m.o} = l), \end{cases} \tag{8}$$

where $P(N_{m.i} < l \mid N_{m.o} = l) = \sum_{j=0}^{l-1} \binom{N_{ot}}{j} \overline{P}_{m.i}^{j} (1 - \overline{P}_{m.i})^{N_{ot}-j}$ and $P(N_{m.o} = l) = \binom{N_{in}}{l} \overline{P}_{m.o}^{l} (1 - \overline{P}_{m.o})^{N_{in}-l}$.

In the above a function of t, $r = v_{max} \cdot t$, determines the period of information exchange, the probability $\overline{P}_{m.i}$ and $\overline{P}_{m.o}$, and therefore the maximum probability with information about both of constant R and active sensor's distance from a sensor deemed to be sleeping. For calculating individual breaking probabilities, Eq. (8) can be modified by replacing the binomial distributions given above with the enumeration of individual probability of each sensor, given by Eq. (6) - (7)

As observed from Fig. 2, $\overline{P}_B$ in Eq. (8) is determined by $\overline{P}_{m.i}$ and $\overline{P}_{m.o}$ which are monotonically descreasing and decreasing, respectively. Therefore we set some predefined threshold value to awaken sleeping sensors, govenred by $\overline{P}_B \geq threshold$.

III. EXPERIMENTS WITH NS2

We used NS2 implementation of CCP [2] as an optimal algorithm to assure K-coverage in a variety of coverage degree cases.

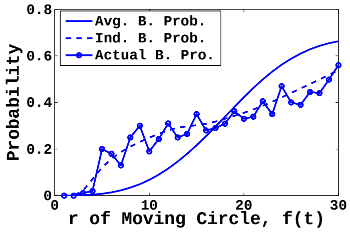


Fig. 5. Comparison of Three Breaking Prob. in 200 runs

Fig. 5 shows the benefit of using average and individual probability in the situation of breaking 3-coverage. Two curve lines explain the mathematical plots for Eq. (8) while the dotted line is made from the actual breaking probability of NS2. As the figure illustrates, there is a gap between average and individual probabilities, and furthermore, the dotted line shows the same behavior of individual probability.

Prob. Scheme:A_0**vs.**A_d	**Coverage Achieved(%)**	**Avg. No. A. N.** †
MRCC w/ A_0	90.6*/94.7**	67.3/89.1
MRCC w/ A_d	96.6/97.3	65.2/84.7

Coverage Scheme	**Coverage Achieved(%)**	**Avg. No. A. N.** †
CCP	93.8*/92.7**	87.1/90.9
MRCC w/ Avg. P.	94.7/93.2	77.6/88.4
MRCC w/ Ind. P.	94.4/94.1	71.1/84.6

TABLE I

COMPARISONS OF A_d VS. A_0 AND AVG. VS. IND. PROB. IN 10 RUNS

* 1-Coverage ** 2-Coverage

† Avg. No. of **A**ctive **N**odes among 120

The simulation results from NS2 in Table I validate the difference in calculation of probabilities between [1] and MRCC, hence proving that our approach is more efficient, and the results are in unison with the probability behaviors obtained in of Figs. 2, 3 and 5. For this experiment, the sensor field under consideration had an area of 400x400. During the simulation of 115 seconds with enough given energy, it was also observed that, after a certain period of time, the average number of active nodes remains almost constant with a standard deviation of a constant factor. This is due to the fact that the cycle of selection and withdrawal of sensors reaches approximate synchrony and hence almost an equal number of nodes are added and withdrawn. The first half of Table I shows the comparison of [1] and MRCC in terms of the number of active sensors and achieved *K*-coverage. Therefore, moving-in probability needs to use the area of outside where moving-in sensors are located. The second half of Table I shows that although the difference in coverage achieved in the three cases is marginal, the number of active sensors for *1*- and *2*- coverage show significant differences, supporting our claim that individual probabilities of moving-in/out is reasonably good in selecting an optimal number of sensors for an energy-efficient coverage scheme.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have addressed the problem of achieving *K*-coverage in the presence of mobile sensors. *K*-coverage is essential in reliable event detection and information transfer, even in the presence of faults. Ensuring *K*-coverage guarantees that a particular area is covered most of time, to a specific degree. Mobility of sensors is one of the major hurdles in achieving *K*-coverage due to the uncertainty in locating a competent sensor for coverage.

In light of the above mentioned problems, we have formulated the average conditional probabilities of moving-in and have achieved a significant reduction in the number of active sensors, as well as a higher achieved coverage. Furthermore, for individual probability, we have articulated the variation of probability as a function of the distance and have improved results than that for the average probability case. Therefore, with fewer numbers of sensors for the same coverage, we believe that a significant amount of power can be saved, leading to the longevity of lifespan of a WSN.

In the future, we will measure power savings obtained by considering battery depletion, as well as how to decide the wake up time based on residual power of a *sleeping* sensor.

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