A Coverage-Preserving and Hole Tolerant Based Scheme for the Irregular Sensing Range in Wireless Sensor Networks

Azzedine Boukerche
PARADISE Research Laboratory
University of Ottawa
Email: boukerch@site.uottawa.ca

Xin Fei
PARADISE Research Laboratory
University of Ottawa
Email: xfei@site.uottawa.ca

Regina B. Araujo
Computer Science Department
Federal University of Sao Carlos
Email: regina@dc.ufscar.br

***Abstract*— Coverage is an important issue related to WSN quality of service. Several centralized/decentralized solutions based on the geometry information of sensors and under the assumption of the disk sensing range have been introduced in the literature. However, the disk sensing range assumption is too strong for applications in the real world and cannot be held in required high accurate scenarios, such as the emergency preparedness class of applications. This paper proposes a new Intersection Point Method (IPM) that extends the disk sensing range assumption to an irregular simple polygon assumption. A Unit Circle Test method was also devised in order to provide a controllable degree of accuracy in the determination of fully covered nodes. By adjusting the radius ”r” of this Unit Circle Test the algorithm can be made tolerant to holes of a certain size. This makes the solution flexible when the degree of accuracy must be controlled. IPM performance was evaluated through a set of simulation experiments implemented in the NS-2 simulator. Those results were compared to the results for the Central Angle Method (CAM)-part of the C-PNSS scheme[6], and the Association Sponsors Method (ASM)-part of the OCoPS solution[1]. The results show that under the simple polygon sensing range assumption our solution can efficiently identify fully covered sensors, discover holes (blind points), and archive better quality results than CAM and ASM. The performance and flexibility of IPM makes it a potential solution for applications that require a high coverage rate with controllable hole tolerance.**

***Index Terms*— coverage, wireless sensor network, central angle, irregular sensing range, intersection point method, unit cycle test.**

I. INTRODUCTION

Wireless sensor networks (WSN) have been a hot research topic in recent years. Advancement in MEMS (Micro Electro Mechanical System) are leading to a world populated by battery-powered, resource-constrained, tiny, and intelligent sensors that are being deployed in a wide range of applications. A fundamental issue in WSNs is the coverage problem, which is considered to be a measure of the quality of service provided by a single sensor or by the entire sensor network.

The most common sensor model used by the majority of coverage related protocols assumes that a sensor can cover a disk centered at itself with a radius equal to the sensing range. However, in most cases, the sensing range is location-dependent and most likely irregular[5]. For example, the photo sensor uses a square sensing range. Moreover, if we consider the effect of reflection caused by boundaries and obstacles, the sensor cannot maintain its disk sensing range unless it is working on an completely flat, boundless area. Such irregular sensing range problems were discussed by Huang and colleagues[5], who pointed out that their K-covered scheme was able to function under an irregular polygon sensing range assumption, but did not literally prove this. When this irregular polygon sensing range problem was applied to region coverage, it became more complicated. The issues mentioned above lead to a challenge that has motivated us: can a distributed scheme that solves the coverage problem under a polygon sensing range without relying on the GPS system be devised? Another interesting aspect of coverage is tolerance to holes (blind areas) since high accuracy coverage is not always necessary (the accuracy for tracking a person is not the same as that for tracking a tank). If we can control the size of holes that can be tolerated, coverage will not be jeopardized, at the same time, network lifetime can be remarkably extended by putting more sensors in off-duty state[20].

In response to the challenge posed above, this paper proposes an Intersection Point Method (IPM) to help nodes locate coverage holes without the limitation of the disk sensing range. Moreover, a Unit Circle Test with adjustable test radius ”r”, was developed in order to enable our scheme to detect holes in a adjustable high precision manner. To avoid excessive energy consumption our IPM method was combined with ALT-E (Alternate Election Algorithm) and the sensing wake-up strategy[1] and implemented and evaluated in the NS-2 simulator.

The paper is organized as follows: Section 2 introduces some related work and motivations. Section 3 presents our Intersection Point Method. Section 4 discusses the experimental results obtained for the performance of our scheme. This is followed by the conclusion.

II. RELATED WORK

The problem of how well a given area can be monitored by the WSN, which is also known as coverage, has recently been tackled by many researchers.

Huang et al.[5] introduced a k-covered problem (where k was a predefined constant) in order to determine whether every point in a given area was sufficiently covered by at least k sensors, while a general solution was presented to keep the network K-covered. Kumar et al.[16] extended this k-covered problem to a k-barrier coverage problem where the wireless sensor network was deployed as a belt so as to guarantee that all crossing paths through the belt were k-covered by the sensor network. The definition of coverage was extended from 2D to 3D by Huang et al. in[17], where a polynomial algorithm was proposed for the 3D K-covered problem. A new notation for information coverage based on accurate estimation was proposed by

This work is partially supported by the NSERC Strategic Grant, the Canada Research Chair Program, the Canada Foundation for Innovation Funds, and the Ontario distinguished Research Award.

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Wang et al.[20]. A point is said to be completely information-covered if enough sensors exits to keep the estimation error lower than a predefined threshold.

A computable deployment threshold is required for increasing density. Based on the probability analysis and certain reasonable assumptions such as a transmission range equal to the sensing range, several solutions were discussed. Gao et al.[18] analyzed the redundancy problem in WSN and provided an easy and relatively accurate estimation concerning the degree of redundancy without the knowledge of location or directional information. A theoretical analysis showed that under the disk sensing range and R_t(Transmision Range) $= R_s$(Sensing Range), if a sensor C was fully covered, at least three and at most five neighbors were needed to cover the sensing area of C. Based on this result, the probability of a completely redundant sensor on a random deployment was given as $1 - n0.609^{n-1} \leq Pr\{A\} \leq 1 - n0.609^{n-1} + \varepsilon$ where $\varepsilon = (0.276)^{n-1}n(n-1)/2$. To keep a sensing network k-covered, Kumar et al.[19] investigated the boundary value under grid, random, and Poisson distribution. A RIS(Random Independent Sleeping) scheme was proposed based on an assigned probability p. It was shown that the network lifetime could be increased by a factor of $1/p$.

Worst and best case coverage were used in order to evaluate the service quality of the WSN. In worst-case coverage, attempts are made to quantify the quality of service by finding areas of lower observability and detecting breach regions. In best-case coverage, finding areas of high observability and identifying the best support and guidance regions are of primary concern. Meguerdichian et al.[11] present a polynomial algorithm based on the Voronoi diagram to locate Maximal Breach Paths and Maximal Support Paths.

Since WSN coverage is narrowly related to connectivity, several papers present solutions that consider the two issues at the same time (ASCENT[2], Span[3], and GAF[15]). In[8], a connectivity-aware coverage solution is presented where coverage is achieved through a probing mechanism that controls the network density. However, this solution does not guard against blind points since there is no guarantee of sensing coverage [13]. Other solutions that provide connectivity-aware coverage include PEAS[7] and[14].

The overlapping redundant nodes in the high-density network have inspired a common solution, the *Off-Duty scheme*, in which each WSN requires an optimal number of nodes to be active while redundant neighbor nodes are off-duty until certain on-duty nodes run out of energy. In order to optimize the number of off-duty sensors and avoid coverage holes, some node selection algorithms were proposed. In[10], Cardei and Du propose a partition protocol that partitions the set of available sensors into disjoint sets such that each set covers all targets in different rounds. A node-scheduling-based scheme that does not require global information was devised by Ye et al.[8]. However, a major drawback to their solution is that breach points are not dealt with. Another distributed, localized algorithm based on node scheduling, called optimal geographical density control (OGDC), was proposed by Zhang and Hou[9]. The algorithm runs in rounds, and at the beginning of each round a set of starting nodes are selected as working nodes. After a back-off time, a starting node broadcasts a power-on message and changes its state to ON. Starting nodes are randomly selected at the beginning of each round so as to ensure uniform power consumption across the network.

Most of the existing coverage schemes are based on disk sensing and depend on probing mechanisms and computing geometry information in order to discover coverage holes and the rate of coverage. [5] and[6] present a simple method to determine a candidate node by calculating the center angles of its neighbors. If such center angles can cover the whole 360° (as the gray cycles B, C, and D shown in figure 1 do), node A is determined to be *fully sponsored*. Because the CAM presented in [6] relies on the R_t(Transmission Range) $= R_s$(Sensing Range) assumption and cannot identify all fully sponsored sensors, an extended method is presented in[1]; this is the Association Sponsors Method(ASM). In the ASM method, the assumption is set as the transmission range equal to twice the sensing range. This can remarkably increase the number of off-duty sensors without holes. The Association Sponsors Method considers any neighbors that share overlapping areas and establishes an association relationship between the high overlapped and low overlapped sponsors, as shown in figure 2, to increase the number of off-duty nodes.

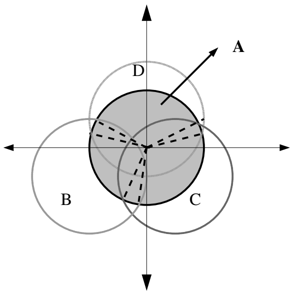

Fig. 1. Central Angle Method

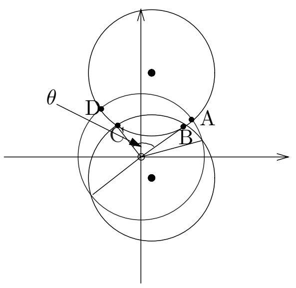

Fig. 2. Association Sponsors Method

Although the methods mentioned above introduce interesting solutions to the coverage problem, most are based on the disk sensing range assumption, which is true only under strict conditions. The following section introduces a novel scheme to WSN coverage, that is based on the irregular polygon sensing range.

III. INTERSECTION POINT METHOD(IPM)

In order to make the coverage scheme more realistic, we propose a new algorithm based on the irregular polygon sensing range to discover fully covered sensors. The solution, called the Intersection Point Method(IPM), is based on the investigation of intersection points of sensing polygons. Our scheme was devised under the following assumptions: (1) The sensors' density is high enough that only part of them are able to monitor the desired region R_m. (2) The Sensing range is a *closed simple polygon* and can be detected by sensors. (3) The Communication range is twice the maximum sensing range.

A. Basic Definition

The basic definitions necessary to understand the IPM scheme are described below and serve as a basis for our proposed solution.

Definition 1: (*Transmission Neighboring Set*): Consider a set of sensors $\{p_1...p_n\}$ in a finite area δ. If we assume that r is the radio radius of a sensor, then the neighboring sensor set TNS_{p_i} of sensor p_i is defined as: $TNS_{p_i} = \{n \in \aleph\,|dis\tan ce(p_i, p_j) < r, p_i \neq p_j\}$

Definition 2: (*Sensing Neighboring Set*): Consider a set of sensors $\{p_1...p_n\}$ in a finite area δ. If we assume that SR is the sensing range of a sensor, then the neighboring sensor set SNS_{p_i} of sensor p_i is defined as: $SNS_{p_i} = \{n \in \aleph | SR_{p_i} \cap SR_{p_j} \neq \phi, p_i \neq p_j\}$

Definition 3: (*Candidate-Fully Sponsored Sensor*): We refer to a node A as a *Candidate* or as *fully sponsored by its neighbors* if the sensing area S(A) is fully covered by S(SNS_A) where SNS_A represents the sensing neighboring set of sensor A, denoted $SNS_A \overset{\text{FS}}{\rightarrow} A$.

Definition 4: (*Simple Polygon*): A polygon *P* is said to be simple (or Jordan) if the only points of the plane belonging to two polygon edges of *P* are the polygon vertices of *P*.

Definition 5: (*Intersection Point of Polygons*): A point p is said to be an intersection point of two polygons if the two edges, which generate such a point, belong to different polygons. If there is no vertex of any other polygon located in exactly the same location, such a point p is called a **Line Intersection Point of Polygons** (LIP). Otherwise, it is called a **Vertex Intersection Point of Polygons**(VIP).

Definition 6: (*Intersection sub-polygon*): A sub-polygon of polygon P is considered to be an Intersection sub-polygon if its vertices belong to the Intersection Points set of P and P's neighbors. If such a sub-polygon exists inside of P we consider it to be a **Breach Intersection Polygon**.

Lemma 1: A polygon P is fully covered by its sponsors only if there is no intersection point $p^{'} \in P$, which is generated by two sponsor polygons P_1, P_2, and it is covered only by polygon P.

Proof : *Let us assume that such a LIP*$^{'}$ *of* P_1 *and* P_2 *exists inside a fully sponsored polygon P. If another point* $p^{''}$ *in P that is excluded in* P_1 *and* P_2 *and the distance* $d_{p' \rightarrow p''}$ *approaches 0, P is a fully sponsored Polygon and* $p^{''} \notin \{P_1 \cup P_2\}$, $p^{''}$ *must be covered by another sponsor polygon* P_3. *When* $d_{p' \rightarrow p''}$ *approaches 0,* P_3 *will intersect with* P_1 *and* P_2 *at* $p^{'}$ *or cover* $p^{'}$. *Otherwise, any points between* $p^{'}$ *and*$^{''}$ *will only be covered by P. That will cause a conflict with our assumption that P is a fully sponsored polygon. Lemma 1 has been proved.*

B. The Intersection Points Method

In the simple polygon world, the relation of polygons is fourfold: inside, overlapping, tilling and intersecting. Because we assume that no two sensors are in the same location, we will ignore the overlapping case and only focus on the other three cases. Based on the Geometry Graph theory, we can determine that polygon A is *inside polygon B* by checking the vertices of polygon A against those of polygon B to see if they are all inside polygon B. If no vertex is outside the range of polygon B, we can say that polygon A is inside polygon B.

The problem of identifying a polygon, that *intersects* with others and is not fully sponsored, is similar to the problem of finding the intersection sub-polygon, which is in polygon B and is only covered by polygon B. The basic solution to finding such a sub-polygon is to identify all intersection sub-polygons and map them against the sponsored polygon. The complexity of such a solution lies in $\mathrm{O}(\mathrm{C}_{n+1}^{2} * m^2 + X * m)$ where X is the number of intersection sub-polygons; m is the average number of edges of the polygons and n is the number of sponsors. Compared to the processing capability of a sensor node, such computations can be too complex to identify all of the breaching holes under the assumption of the polygon sensor range. Thus, we must reduce the complexity of such solution in order to make it more realistic. Further research is encouraged by Lemma2 as follows:

Lemma 2: If a polygon P intersects with its sponsors and is not fully sponsored, there must exist an intersection polygon inside P whose vertices are composed of the intersection points of P and its sponsors.

In other words, if we can identify an intersection point in polygon P adjoined to any area that belongs only to P, we can say that P is not fully sponsored. Actually, for the off-duty scheme we are more interested in the existence of such a breach polygon than in obtaining all of the information concerning its vertices. Thus, we developed the following algorithm to identify a non-fully sponsored sensor:

Algorithm III-B—Intersection Point Method

```
FOR (each node q ) {
Investigating all of the intersection points
with neighbors by a line sweep algorithm;
Removing intersection points uncovered by P;
Finding an intersection Point (IP) that adjoin
to a breach intersection polygon;
If there is no such IP,
The tested sensor is fully sponsored. }//end of loop
```

The key issue of this algorithm is the method for testing the intersection point that adjoins a breach intersection polygon. In order to resolve such a problem, we devised a new method: the Unit Circle Test, described in the next section, which is based on lemma 2.

C. The Unit Circle Test

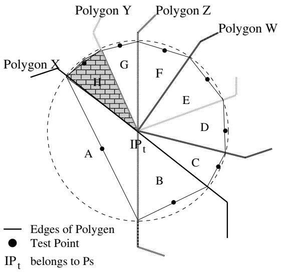

Fig. 3. Unit Circle Test for P_S

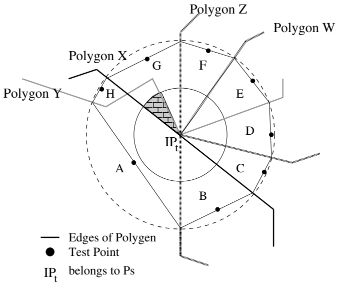

Fig. 4. Holes Tolerant

In order to find a non-fully sponsored node, we developed a simple method called the Unit Circle Test. Assuming that sensing polygons W, X, Y, and Z intersect at intersection point $IP_t \in P_S$, we draw a small enough Test Circle centered at IP_t in order to identify whether P_S is a fully sponsored node. The intersection edges of IP_t will cut this Test Circle into smaller pieces, as shown in figure 3, which means that there are no other sub-polygons in such pieces. If IP_t is adjoined to a breach area, at least one piece will belong to a breach sub-polygon. Thus, we can pick up points from each piece generated by the Test Cycle, such as the points A to G in figure 3, and test whether they are inside polygons W, X, Y, and Z. If any point from A to G belongs only to polygon P_S, polygon P_S is considered to be not fully sponsored. In order to select proper points, we picked up the test points as follows: as shown in figure 3, the Test Circle intersects with all intersection edges of IP_t. We denote such new intersection points generated by the Test Circle as p_{ui}. We connect p_{ui} clockwise and pick up the middle point of connection line segment as the test point(TP). As we know, we can look at each of the pieces generated by the Unit Circle Test as a *Convex Curve Polygon*, which means that test point TP will be located exactly in each of the pieces. Thus, if one TP belongs to polygon A, we identify polygon A as a non-fully sponsored node.

Tolerance to Holes:

In some application scenarios, holes can be tolerable. Thus, it would be interesting if we could control the degree of hole-tolerance according to the application requirements. Most existing coverage algorithms ignore this requirement or do not support hole tolerance. In IPM, the hole tolerance control can be supported by adjusting radius r of the Test Circle - we can allow the algorithm tolerant holes that are not larger than the Test Circle. Figure 4 shows that when we enlarge the Test Circle from the solid line circle to the dash line circle, the breach polygon which is created by polygons X and Y and is marked as the black brick area, is ignored.

D. Comparison of IPM with Other Methods

IPM is a novel method to identify fully sponsored sensors. In order to demonstrate the strength of IPM, IPM will be compared with the following existing solutions: Probing [8], the Central Angle Method(CAM) [6], and the Association Sponsor Method (ASM)[1]. Probing is a basic method for the coverage problem, that does not consider the sensing range and only turns on sensors when there are no other sensors in its communication range. Probing runs very quickly and is easy to implement; however, it does not deal with holes at all. The Central Angles Method introduces a novel idea that considers the existence of holes by identifying fully sponsored sensors locally through low complexity computing. This method, however, cannot guarantee the identification of holes and will cause a connectivity problem when nodes run out of energy.

TABLE I

COMPARISON OF FULLY SPONSORED DISCOVERY METHODS

	IPM	ASM	C-PNSS	Probing
Sensing Range	Any Simple Polygon	Disk	Disk	Any
Identification Methods	Unit Circle Test	Association Sponsor	Central Angles	Probing
Precision	Radius of Unit Circle	X	X	X
Hole-Tolerant	Controllable	Uncontrollable	Uncontrollable	Uncontrollable
Complexity	$\bigcirc(Xk^2m + nm\log(nm))$	$\bigcirc(n*m^2+n)$	$\bigcirc(n*m^2+n)$	$\bigcirc$(n)

(Where n is the average number of neighbors, m is the average number of edges of a sensing polygon,
and k is the average edges involved in an intersection point,X is the total intersection points in the polygon P.)

In order to maintain the network connectivity and take full advantage of the Central Angles Method, the Association Sponsor Scheme (ASM) was devised and described in [1]. ASM doubles the transmission range of the sensing range and considers areas that overlap with all neighbors - neighbors with a low overlap area are associated with neighbors with a high overlap area, and this relationship is considered as a combination. Our Intersection Point Method is compared to the Probing, CAM, and Association Sponsors with relation to the sensing range assumption, precision, hole-tolerance, and computing complexity. Table I shows the comparison of the methods in the simulation experiment described in the following section. As shown in Table I, IPM shows good potential in most of the aspects considered, except high computing complexity, which is caused mainly by the simple polygon assumption. The computing complexity can be reduced through a stronger assumption, such as the disk sensing range or the convex polygon sensing range. The next section describes the simulation environment and performance evaluation results obtained.

IV. PERFORMANCE EVALUATION AND SIMULATION EXPERIMENTS

In order to evaluate the performance of our scheme and compare it to both the Association Sponsor and Central Angles [6], a set of simulation experiments were carried out. These are described in the following section.

A. The Simulation Environment

The number of sink and sensors, that were randomly deployed in the $50m \times 50m$ area, varies from 100 to 300. Each sensor's sensing range is considered to be a simple polygon and varies from 5 to 10 meters in size. For calculating coverage, the monitored area was divided into $1m \times 1m$ grids in which events were generated every 0.5 second at the cross points. We estimated the initial network coverage as 100% and considered only the holes generated by turned-off sensors and the coverage reduction caused by both off-duty and out-of-energy sensors.

By determining how many events are detected by on-duty nodes, we can roughly calculate the coverage rate. If an event source which exists in the range of the initial sensing coverage, cannot be detected by any on-duty node, we call such an event source *hole or blind point*. How well the scheme prevents the occurrence of blind points indicates the coverage-preserving ability of the scheme. In order to illustrate the benefits of applying IPM to the off-duty scheme, we implemented IPM with the ALt-E algorithm and the sensing wake-up strategy[1]. The results obtained were compared to the results obtained with the ASM which is presented on paper[1]. The simulations realized tries to prove that our scheme can efficiently identify all of the candidates and locate all of the breach points caused by turned-off and out-of-energy sensors. The simulation tests performance under the equilateral triangle sensing range, the star sensing range, and the Circumscribed Disk sensing range on the following two aspects, respectively: Candidates & Errors, Hole-Tolerant.

B. Simulation Results

•**Candidate & Errors:** In this section we evaluated how well the IPM identified the fully-sponsored sensors. We ran the algorithms separately under the equilateral triangle sensing range, the start sensing range, and the disk sensing range and compared the number of identified candidates and errors. The performance of all algorithms was good under the *disk sensing range*, and the IPM achieved the same result as the ASM on average. In some cases the result of IPM even better than the ASM. It is interesting to observe that when the algorithms were applied to irregular sensing polygons such as triangles and stars, ASM and CAM identified an abnormally higher number of candidates than the IPM, as shown in figures 5 and 7. When we matched the results of IPM, ASM, and CAM, the latter two algorithms showed a high rate of error-over 20% -as shown in figures 6 and 8. It is obvious that the algorithms based on the Central Angles Method did not work well under the irregular polygon sensing range since they were not able to deal with a scenario where two polygons intersect at more than two points. Such simulation results may seem unfair to some extent because we forced the CAMs to work under situations for which they were not suited. In order to ensure the validity of such a comparison, we tested the Central Angles Method and the ASM under circumscribed circles instead of simple polygons; the results are shown in figures 9 and 10. The results are better than the previous figures but the error rate is still higher than 15% percent.

• **Holes-Tolerant:** In some cases, holes that are lower than a controllable size can be tolerated. In this section, we adjust the radius of the Test Circle from 0.1m to 3m and record the increase in the number of candidates and holes. The result illustrated in figures 11 and 12, shows that when the radius reaches 0.5m, the number of identified candidates is 64 and the number of tolerated holes whose radius is lower than 0.5m is 5. When the radius reaches 2m, the number of holes increases to 210. In other words, when we tolerate holes whose radius is lower than 0.5m, The IPM can identify 20% more candidates and generate only a low number of small holes.

V. CONCLUSION

This paper presented a new, fully-sponsored sensor discovery scheme, the Intersection Point Method (IPM), which works under the irregular sensing range and can efficiently increase the accuracy of the discovery method through a Unit Circle Test. By adjusting the radius ”r” of this Unit Circle Test, the scheme can be made tolerant to holes of a certain size, making the solution flexible when the degree of accuracy must be controlled. The IPM was compared to the ASM and CAM algorithms under the Triangle and Star sensing range in terms of degree of correctness in identifying candidates. The error rate obtained show the superior potential of IPM in term of maintain a high rate of coverage in WSN under an irregular polygon sensing range. They also show that the Central Angles Method does not meet coverage quality requirements under the irregular sensing range even when a circumscribed circle is assumed. Through an adjustable Test

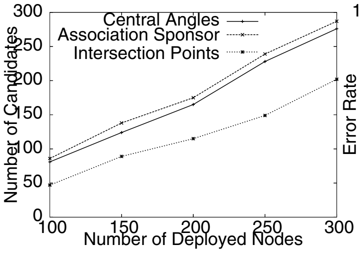

Fig. 5. Number of Candidates Vs. the Number of Deployed Nodes; Equilateral Triangle Sensing Range

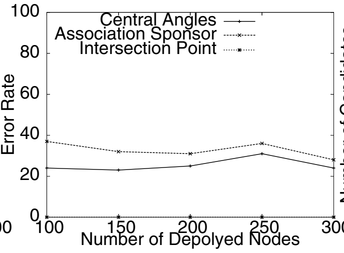

Fig. 6. Number of Errors Vs. the Number of Deployed Nodes; Equilateral Triangle Sensing Range

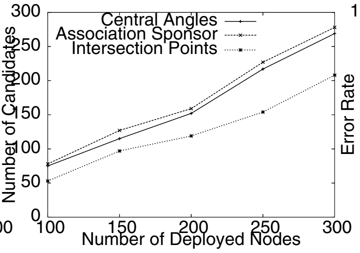

Fig. 7. Number of Candidates Vs. the Number of Deployed Nodes; Star Sensing Range

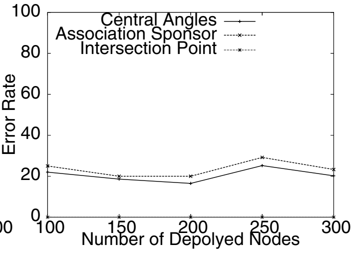

Fig. 8. Number of Errors Vs. the Number of Deployed Nodes; Star Sensing Range

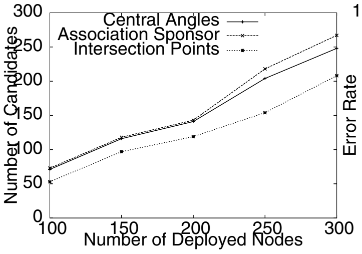

Fig. 9. Number of Candidates Vs. the Number of Deployed Nodes; Circumscribed Circle of Star

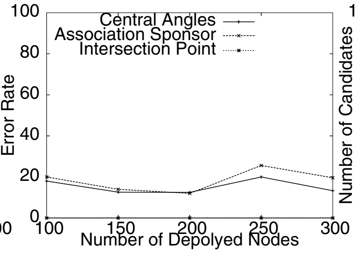

Fig. 10. Number of Errors Vs. the Number of Deployed Nodes; Circumscribed Circle of star

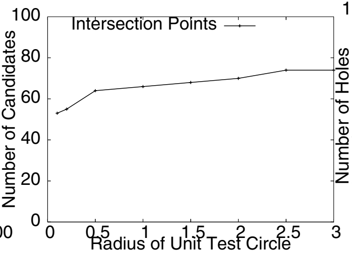

Fig. 11. Number of Candidates Vs. the Radius of the Test Circle

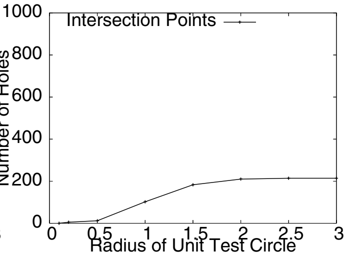

Fig. 12. Number of Holes Vs. the Radius of the Test Circle

Circle, we demonstrated that by tolerating holes in a controllable manner, we can efficiently increase network lifetime under a high rate of coverage. Moreover, a controllable tolerance to holes makes IPM a flexible solution when accuracy can be relaxed. By combining IPM with ALT-E[1] and the sensing wake-up strategy, our scheme extends network lifetime while guaranteeing initial coverage. Our solution was compared with CAM and ASM schemes in order to illustrate the degree of correctness in terms of identifying candidates.

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