Improved Coverage Through Area-based Localization in Wireless Sensor Networks

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***Abstract*—Ensuring area coverage is one of the key requirements of wireless sensor networks (WSNs). When nodes are randomly placed in the area of interest, redundancy is often provisioned in order to lower the probability of having voids, where part of the area is not within the detection range of any sensor. To extend the lifetime of the network, a duty cycle mechanism is often applied in which only a subset of the nodes are activated at a certain time while the other nodes switch to low-power mode. The set of active nodes are changed over time in order to balance the load on the individual sensors. The selection of active nodes is subject to meeting the coverage requirement. Assessing the coverage of a sensor is based on knowing its position. However, localization schemes usually yield a margin of errors which diminishes the coverage fidelity. Conservative approaches for mitigating the position inaccuracy assume the worst-case error across the network and end up activating excessive number of nodes and reduces the network lifetime. In this paper, we present an approach for estimating a bound on the maximum error for the position of each sensor and propose a distributed algorithm for achieving high fidelity coverage while engaging only a subset of the sensors. The simulation results confirm the performance advantages of our approach.**

***Keywords*—Coverage, Range-free localization, Wireless sensor networks.**

I. Introduction

Wireless sensor networks (WSNs) have gained popularity in recent years due to the growing list of applications that practitioners envision these networks can effectively serve [2]. Most notable among the possible applications are those serving in unattended setups where humans presence is risky and/or impractical. Examples include surveillance of vast borders military reconnaissance, and security monitoring of strategic installations. In these applications, battery-operated sensors are deployed in an area of interest to monitor their surroundings and report their findings to a base-station. The main metrics for assessing the quality of service of WSNs is the level of coverage and the longevity of such coverage. The coverage of a WSN can be defined as the fraction of the area that falls within the detection range of sensors. On the other hand, the longevity of the WSN service depends on the lifetime of the individual nodes to ensure the continuity of the area monitoring.

To boost the lifetime of the individual sensors, energy aware techniques are often employed in managing the operation of WSNs. One of the popular energy-saving strategies is to selectively engage a subset of the sensors at a particular time and rotate the area monitoring duties among the entire set of nodes [3]-[6]. Basically some nodes will be activated to serve for certain duration while the rest are turn to a low-power sleep mode in order to conserve their batteries. Then, the sleeping nodes get activated to allow the other nodes to be disengaged and turn to sleep mode. The main issue in scheduling such rotation is ensuring connectivity and coverage. Since the communication range is often larger than the coverage range of a sensor and the scheduling problem becomes mostly constrained by the coverage requirements imposed by the applications.

Ensuring full area coverage depends on the sensors location and the detection range. For many WSNs, nodes are randomly spread in the area and therefore redundant sensors are deployed in order to maximize the likelihood that not having voids where part of the area does not have any sensor. Most of the coverage protocols found in the literature assume that the sensors location information is perfectly accurate [7]. Unfortunately, none of the existing GPS-free localization techniques for WSN can provide such accurate information about sensors position which can considerably affects the correctness of the calculated coverage metric. Typically the bulk of sensor nodes are not equipped with GPS receivers due to the small form factor and low cost constraints. Thus, ruling out localization errors while scheduling sensor activation is a shortcoming in published schemes since it cannot guarantee the absence of coverage holes.
There have been some attempts to factor in localization errors while checking the coverage. The location error is assumed to be predefined and based on the probabilistic model [8] or a fixed threshold [9]. However, since accurate information about the error at each sensor level is not factored in, the coverage can be either over- or under-estimated. On the other hand, some recent work [10][11][12], has proposed a location-free coverage methodology. Instead of relying on knowing the sensors position; only the distance or the orientation between neighboring is employed in estimating coverage. However, the distance is determined based on the properties of the received signal strength and is thus prone to error, which still diminishes the accuracy of the coverage assessment.

In this paper we highlight the impact of localization error on the fidelity of the coverage and then propose a scheme for mitigating such negative effect. The main contributions of our work are as follow. First, we leverage our prior work on range-free localization [13] and present a mechanism for determining the maximum location error at each sensor. We then show how the inaccurate sensors location information yield incorrect sensors coverage estimate and outline a procedure that uses the information about the maximum location error to assess the achievable sensors coverage. Finally, we present a novel distributed algorithm for meeting the Coverage requirements while reducing the number of active nodes subject to Inaccurate sensor Positions (CIP). Our proposed algorithm takes advantage of the Voronoi-cell based network subdivision made by the localization algorithm to allow the node activation and coverage assessment procedure to run concurrently at each network subdivision. This expedites the node activation/deactivation process and enables the network to quickly adapt to changes in the nodes state. The performance advantage of our algorithm over competing schemes is validated through simulation. To the best of our knowledge no prior work has estimated a tight bound on the maximum location error and employed such a bound in efficiently achieving the coverage requirements.

The rest of this paper is organized as follow. Section II summaries the related work in literature. Section III discusses the effect of localization error on coverage and states the assumptions. Section IV describes the proposed CIP algorithm. The simulation results are presented in Section V. Finally, Section VI concludes the paper.

II. Related Work

Area coverage is an important performance metric for WSNs and has thus received significant attention from the research community [7]. Published work can be categorized based on the solution methodology into triangular lattice [6], perimeter coverage [8] and Voronoi diagram [9]. Regardless of the used methodology, most of the proposed protocols achieve a full coverage in the case of accurate sensors location, i.e., actual sensors coverage. Given the scope of the contribution, we focus on prior work that considered location inaccuracy.

In [6], the authors propose a probabilistic coverage protocol (PCP) to ensure all parts of the monitored area are within the detection range of at least one sensor. PCP aims to extend the network lifetime by determining the minimum set of sensors which ensure coverage while keeping the others sensors in sleep mode. The main idea behind PCP is based on the observation of [14] that the optimal coverage is achieved when placing the sensors on the vertices of a triangular lattice whose side equals $\sqrt{3}R_s$, where R_s is the sensing range. In a randomly-deployed sensor network, PCP tries to construct an approximate triangular lattice. PCP operates iteratively in rounds; in each round more sensors are activated until the desired coverage is reached. When the nodes position is inaccurate, the authors hint that PCP would increase the number of activated nodes at each round. No details are provided on how to activate sensors in this case and how the new coverage level is assessed.

The focus in [8] is on the problem of achieving optimal coverage assuming a known probability distribution of localization errors. Optimal in this context means using the least count of active nodes for having the area fully covered. Since no precise information about the minimum and the maximum location error are available, the authors propose two coverage assessment methods, namely, optimistic and conservative. The optimistic approach strives to limit energy consumption by activating only few sensors at the expense of a degraded coverage. The conservative approach tries to ensure full coverage by activating more than necessary sensors. The optimistic (conservative) approach achieves its goal by assuming that the actual distance between neighbors is smaller (greater) than estimated.

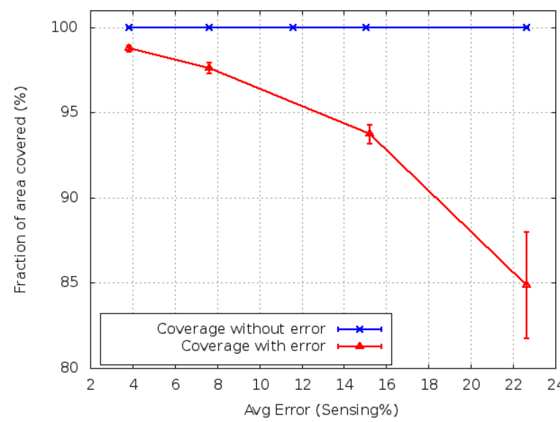


Fig. 1. Quantifying the effect of localization errors on coverage

Chen et al. [9] employ Voronoi diagram in order to assess the coverage overlap between adjacent sensors and pick certain node to switch to sleep mode. In this scheme, a sensor is a sleeping candidate if(1) it covers all the vertices of its Voronoi cell, and (2) when a sensor goes to sleep the vertices of the new Voronoi diagram that are covered by its sensing range must also be covered by other sensors. To mitigate the position inaccuracy problem, the location estimates were assumed to be uniformly distributed in a circle centered at the actual positions with radius r. We argue this is unrealistic assumption and devise a tight bound on the maximum localization error. We should mention that Voronoi diagram is used in our approach to support scalability and expedite the topology adjustment when CIP is re-executed to balance the load on the network nodes. Moreover, the Voronoi diagram is formed by the underlying localization algorithm at the level of anchors and will be just reused by CIP without introducing additional overhead.

III. Problem and System Model

A. *Effect of Localization Error on Coverage*

The main goal of this paper is to deal with the potential of having coverage holes when sensors positions are inaccurate. This is motivated by the fact that the coverage confidence can be degraded when ignoring or imprecisely estimating the location error. Fig. 1 demonstrates the impact of the inaccurate position on the fraction of the covered area. The plot is obtained by executing the protocol in [6] for a network of 700 sensors that are deployed in area of size $250m \times 250m$ following a uniform random distribution. The communication and sensing ranges are set to $40m$ and $20m$, respectively. The figure reports the fraction of the area covered when varying the location error as a fraction of the sensing range. The results show that more than 15% of the area is not covered even when the error level is not exceeding 25% of the sensing range.

Unfortunately, localization errors are inevitable in wireless sensor network and none of the existing coverage algorithms that opts to extend the network lifetime by limiting the activation of sensors is capable of guaranteeing a full coverage under such constraints. Mitigating this problem by assuming a fixed error is not effective given the variability of the localization errors experienced by the individual nodes; a coverage hole will exist if a node suffers a larger error, while an overestimate can lead to activating unnecessary nodes. In this paper, we show that we can efficiently mitigate to such a coverage problem by, first getting an accurate assessment of the localization error of the individual sensors, and secondly proposing a distributed scheme that use this information to ensure full coverage.

The idea behind our solution is the use of an area based localization algorithm [13] that can accurately determine the maximum error that the position of each sensor is subject to. We then devise anode activation protocol by employing the per-node localization error in order to avoid coverage holes. To ensure scalability and expedite the node scheduling process, we propose a distributed algorithm based on Voronoi diagram, where sensors belonging to the same Voronoi cell start the coverage protocol independently.

B. System Model

We consider a WSN that consists of $N+k$ nodes. Let $S = \{S_1, S_2 S_N\}$ be the set of sensors and let $A = \{A_1, A_2, A_k\}$ be a set of anchors in the two dimensional squared network area, where $N >> k$. An anchor is a sensor node that precisely knows its position either by controlled placement or by equipping the node with a GPS receiver. The Voronoi cell of an anchor A_i with respect to a set of anchors, denoted $VN(A_i)$, is the set of points in the plane which are closer to A_i than any anchor in $A_n A_i$. If the Voronoi cell of each anchor is constructed with respect to all other anchors in the network, the set of Voronoi cells will be a partition of the area of interest. Each sensor S_i, after executing the localization protocol, knows its residence area RA_{S_i} and the Voronoi cell of its nearest anchor $VN(A_j)$ that contains RA_{S_i}, where A_j belongs to A. A perfect disk sensing model is assumed where each active sensor has a sensing radius of R_s. An active sensor can reliably probe its environment within the disk centered at its position. Each sensor node is assumed to be operable in active and sleep mode. The latter implies that the node is consuming minimal energy, and thus it is advantageous to keep a node in such a mode in order to extend its lifetime.

IV. MITIGATING LOCALIZATION ERRORS

Before presenting CIP in detail, we first give a brief overview of the underlying localization algorithm and analyze the maximum error.

A. Underlying Localization algorithm

Localization methodologies can be generally classified into range-free and range-based. The latter works by measuring point-to-point distance or angle between each pair of communicating nodes or between a node and an anchor (a reference node with a known position). On the other hand, range-free localization do not require point-to-point measurement and generally uses connectivity to estimate an approximate distance or uses received signal strength indication (RSSI) information to infer the near far relationships between sensors and anchors. Most localization schemes provide the coordinates of a node relative to the anchors without bounding the error that these coordinates may be subject to in the x- and y-directions. Area-based localization is special class of range-free methodologies in which the localization process determines a residence area within which the node is located. Obviously, the smaller the area is, the better the localization accuracy will be.

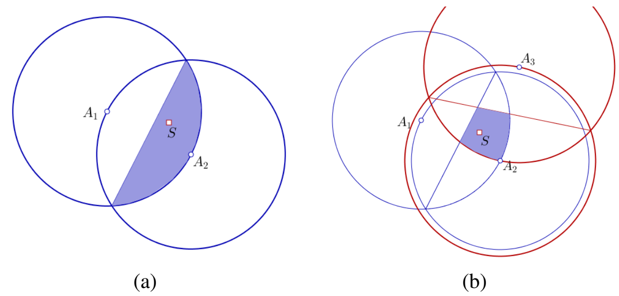


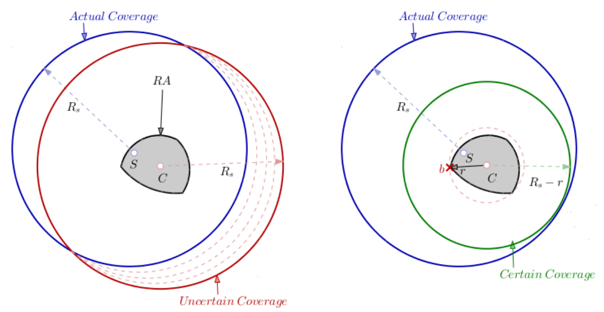
Fig. 2. Illustrating the residence area in HSL using: (a) two anchors, and (b) three anchors

In [13], we have developed HSL, a localization algorithm that yields a residence area shaped by the intersection of multiple half-symmetric lens. The protocol starts by subdividing the network using the Voronoi diagram made up with the actual coordinates of anchors nodes. Based on the RSSI information, each sensor can deduce its nearest anchor and consequently the Voronoi cell where it is located. Each sensor then draws a set of symmetric lens area using the position of its neighboring anchors and checks its presence within each of them. The final sensors residence area is refined by intersecting all the half-symmetric lens areas where the sensor is located and the Voronoi cell of its nearest anchor. Fig.2 illustrates the residence area of a sample sensor after running HSL. In [13], HSL is shown to outperform all existing area-based location schemes. In the next subsection, we accurately determine the maximum error of a location estimate by analyzing the residence area of HSL.

B. Estimating Maximum Localization Error

Any localization algorithm returns an estimate about sensor position. For example, HSL locates a sensor (s) within a region called residence area (RA) (see Fig. 3(a)) and return the centroid (c) of that area as its location estimate. However, if a sensor s calculates its coverage based on the estimated position c, the resulting coverage is incorrect as shown in Fig. 3(a), where R_s is the sensing range and the blue circle define the area covered by s and the red circle indicates what the coverage is when c is assumed to be the position of s. The shaded red area is not actually covered by sensor s, and this constitutes a region with coverage uncertainty. In order to overcome the coverage uncertainty problem, we will show how our area based localization algorithm can be used for this purpose. In HSL, the sensor's residence area represents the actual region where the sensor is located. Therefore, the location error can be easily calculated as the maximum distance between the estimated position and the farthest boundary points of the sensor's residence area.

Let us consider a similar example in Fig. 3(b), where r



(a) (b)

Fig. 3. Sensors coverage estimation: (a) Uncertain coverage without adjustable sensing range. (b) Certain coverage range using an adjusted sensing range

is the distance between the centroid of the residence area (c) and the farthest boundary point (b) of the residence area. To determine the certain coverage of s based on its estimated position c and its residence area RA we have to adjust the radius of the sensing disk, centered at the estimated position c, in such a way that the new calculated sensing disk does not exceed the actual coverage of s (the blue circle in Fig. 3(b)). It is clear that the farthest possible position of s from c is point b. In this case the sensing radius must be $R_s - r$ in order to ensure that the coverage(green circle in Fig. 3(b)) is not over-estimated. The calculation of r can be obtained through analytical geometry or simply approximated through mapping the uncertainty area to a rectangular grid [13]. In the next subsection, we employ such range adjustment to assure area coverage while engaging only a subset of nodes.

C. Detailed CIP Operation

CIP factors the estimate for the maximum localization error of each sensor in the node activation process. In addition, CIP opts to ensure scalability for large networks. A node activation using the procedure in CIP, or other published schemes, is an iterative process and may takes N iterations to conclude, where N is the number of sensors. This can be too slow for very large networks and for real-time applications for which any change in the WSN topology should be quite fast in order to avoid disrupting the network operation. CIP achieves such a design goal by partitioning the network into clusters for which the node activation process runs independently within each cluster. Better yet, CIP leverages the Voronoi diagram formed during the execution of HSL in defining the cluster boundaries. Furthermore, CIP takes advantages of the anchors and utilizing them in triggering the node rotation in order to balance the load on the individual sensors and boost the network lifetime. Relying on the individual anchors can eliminate the need for clock synchronization among the network nodes. This makes CIP lightweight in terms of the imposed resource overhead. The following explains the various steps, which are summarized in Fig. 4:

1) Adjusted coverage range calculation: Before starting the coverage protocol, each node must apply HSL to calculate its new adjusted sensing coverage range as discussed in the previous section. Node i with maximum error r_i, its new adjusted coverage range is $R_{s_i} = R_s - r_i$. After that, the node

Initialization phase:(performed once)
R_{s_i} : the sensing coverage range
State=Sleep

Localization phase: (performed by the localization algorithm)
$(x_i, y_i) = Location\_Estimate\ (i)$
A_i = nearest anchor
$N_i \leftarrow \emptyset$ {Set of neighbors of sensor i in the same Voronoi cell}
$r_i = MaxError(i)$

Coverage adjusting phase:
$$Effective\_Coverage\_Range\ (R_{s_i}) = R_s - r_i$$
Broadcast message containing: (x_i, y_i) ,$A_i$and R_{s_i}
If received message from neighbors j in the same Voronoi cell
Append to $N_i\left((x_j, y_j), R_{s_j}\right)$
End if

Activation phase:
If activation message arrive from neighbor in N_i or anchor A_i
State=Active
$$Min\_R_{s_i} = Min(R_{s_k}), R_{s_k} \in N_i$$
Update N_i by deleting all neighbors that have $R_{s_i} > Min\_R'_{s_i}$
$(v_1, v_2, v_3, v_4) = Hexagon\left((x_i, y_i), Min\_R_{s_i}\sqrt{3}\right)$ // calculate the coordinates of the hexagon centered at sensor i position of side equal to $Min\_R_{s_i}\sqrt{3}$
For each hexagon vertex $v_j\ (1 \le j \le 6)$
Select from N_i the nearest sensor to v_j
Send an activation message to the selected sensor
End for
End if

Fig. 4. Summary of different CIP steps

broadcasts a coverage message to its neighbors including its location estimate, its nearest anchor identifier, and its adjusted coverage range R_{s_i}. Upon receiving the coverage messages from all its neighbors belonging to its Voronoi cell, node i stores the information about the smallest adjusted coverage range; we denote the minimum adjusted range by $Min(R_{s_i})$. The position of its neighbors that have an adjusted coverage range less or equal than $Min(R_{s_i})$ are also stored in a candidate nodes list. This information will be used to calculate the triangle lattice and activate new nodes, as we explain.

2) Network Clustering into Voronoi Cells: HSLoperates by forming a Voronoi diagram using the anchors(see Fig. 5). The formed Voronoi Cells will define for each sensor which anchor is the closest. Sensors within a Voronoi Cell collaboratively apply the node activation procedure to ensure intra-cell coverage. Obvious, the union of all Voronoi Cells is the area of interest and thus covering the individual cells would meet the coverage requirement for the network.

3) Activator node selection: In each Voronoi cell, the anchor node would select one node in its cell at random to act as the activator node. Contrary to the published node activation protocols such as PCP [6]that require inter-node coordination and clock synchronization for picking an activator node, the presence of anchors and the formation of Voronoi cells in CIP

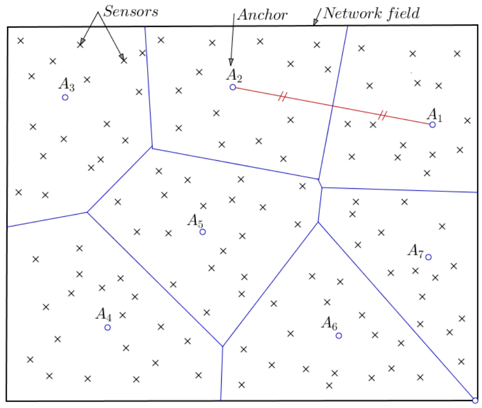


Fig. 5. Network field subdivided into 7 Cells using Voronoi Diagram. The formation of the Voronoi diagram is done through the coordination among the anchors

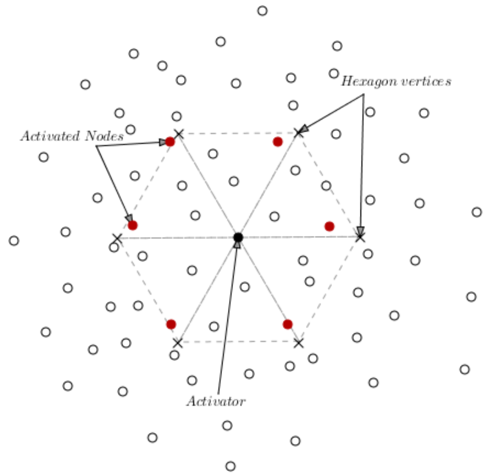


Fig. 6. The activation process based on triangular lattice

make this requirement unnecessary. This enables the coverage protocol to start simultaneously at different cell level, and allow quick convergence of the node activation process.

4) Node activation: When the activator node i is first selected, it, in turn, tries to activate the smallest possible set of nodes that ensure coverage. For this purpose, the coverage protocol tries to activate a set of nodes in such a way that form an approximate triangle lattice. Such activation criterion is based on the observation that the optimal node placement to cover an area of interest is by placing the nodes at the vertices of the triangle lattice of side equal to $\sqrt{3}R_s$, where R_s is the sensing coverage range in [15]. However, previous work, e.g., [6], that use this methodology to calculate the network coverage assume accurate nodes positions. Our activation process is based on the same methodology and handles the inaccurate position of sensor nodes. To activate sensor nodes, the activator calculates the vertices of the hexagon centered at its estimate position with side equal to the maximum possible separation between two activated nodes (see Fig. 6). In the presence of location error, as we have seen in the previous section, the sensing range is adjusted and is not the same for all nodes. Therefore, the side of the triangle lattice must be also adjusted to avoid coverage holes.

To set the length of the triangle side we propose two methods. First method consists to set the triangle side based on the minimum adjusted coverage among all the neighbors of the activator node. This would ensure that any neighbor that is near a vertex of the activator hexagon can be selected without worrying about coverage holes. Such a method boosts the activators chances in finding a node nearest the hexagon vertices, especially in low-density network setup. However, this may yield to relatively higher number of activated nodes as the size of the triangle lattice is set to a minimum. The second method sets the triangle side based on the average of the adjusted coverage among all the neighbors of the activator. In this case the chance of finding a node nearest a hexagon vertex diminishes in comparison to the first method, especially in sparse networks; however in dense network this method can considerably decrease the number of activated nodes. An evaluation and comparison between the two methods is provided in Section V.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of CIP, in term of the fraction of area covered and the percentage of activated sensors. We evaluate the effectiveness and efficiency of CIP under varying levels of inaccuracy in sensor location. We compare the performance of CIP to that of PCP[6] in a perfect error-free scenario and in presence of localization errors without employing any mechanism to handle location inaccuracies. For the simulation, we use the following parameters. We deploy 700 sensor nodes using a uniform random distribution in an area of $250m \times 250m$. The network density is changed by varying the number of sensors. We deploy 40 anchors to allow sensor nodes to get their estimate position with a low error margin, i.e., small residence area. The anchors subdivide the network into 40 Voronoi cells.

The sensing and the communication ranges are fixed at $20m$ and $40m$ respectively, which are relatively small compared to the area of interest and enables multi hop communication. In addition, the sensing range is small enough to allow fine-grained coverage analysis and enable the effectiveness of the activation process to be assessed. We repeat each simulation 50 times and we plot the average and the corresponding 95% confidence interval of the results. Each sensor can have different location error that is determined by the localization algorithm.

A. Fraction of area covered

Fig. 7 plots the fraction of the area covered under CIP and PCP, with and without error, for different node densities. We use PCP without error as a reference for how far the results could be in the perfect scenario where all locations are accurate. From the figure, it can be observed that as the node density increases the coverage grows. This is expected and due to the fact that more sensors can be found near the vertices of a hexagon, which is not the case with low node density. However, when positions are inaccurate PCP leaves out a significant part of the area uncovered, especially for low density scenarios; this is due to the inaccurate localization which leads to not picking the right nodes to activate.

In Fig. 8 we plot the fraction of area covered for different

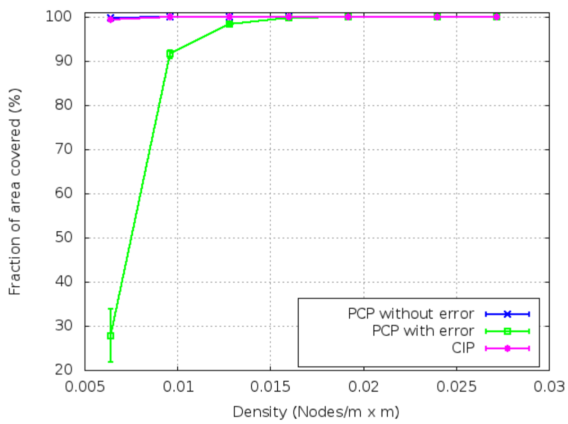


Fig. 7. The fraction of area covered while varying the node density

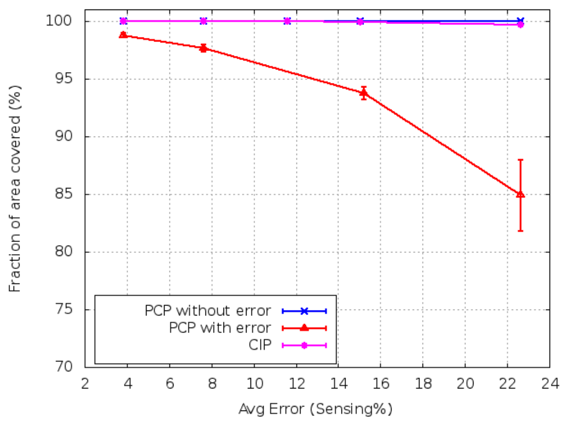


Fig. 8. The effect of localization error on coverage under CIP and the baseline approaches

amounts of localization errors. The errors are captured as a percentage of the sensing range in order to indicate the significance and scale. The values of error in the graph correspond to the level of inaccuracy averaged over the entire node population in the network. Fig. 8 shows that without factoring the localization errors, the coverage degrades significantly, while remains stable and near 99% in our scheme.

B. The percentage of activated sensors

The number of activated sensor is also tracked in the simulation and is reported in Fig. 9 as a percentage relative to the total number of nodes. The goal is to study how the localization error relates to the number of activated nodes We note also that CIP requires more nodes to achieve full coverage than the perfect scenario, which is expected as the error grows the uncertainty region for the individual sensors and reduces the size of the triangular lattices and thus more node are required to cover the overall area. The results show that the percentage of active nodes grows significantly when the localization error increases almost linearly and the gap between CIP and the error-free case widens. It is worth noting that the number of active nodes will not change in PCP if the localization errors are not factored in and thus the corresponding curve in the plot stays flat (constant number of

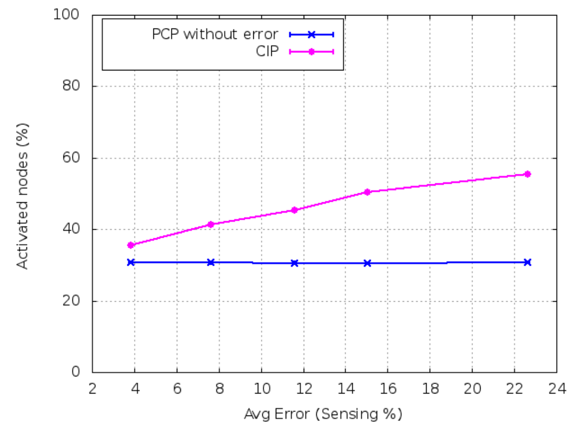


Fig. 9. The effect of average localization error on the fraction of activated nodes required for achieving full area coverage

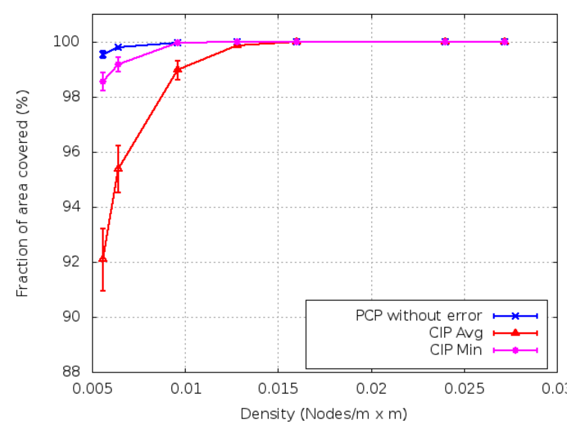


Fig. 10. Comparing the effect of using minimum and average errors on coverage as the node density changes

active nodes). We also note that we have omitted the graph of PCP with error since PCP does not factor in localization errors in the coverage process and thus it cannot get compared to CIP in that regard.

C. Comparing the methods for adjusting the triangle side

As discussed in section IV, two methods can be applied in factoring in the localization error while setting the side of the triangular lattice, namely, using average or minimum error among the neighbors. To assess which method is better, we have run simulation experiments and plotted the results in Fig. 10 and 11. For the results of Fig. 11 we simply assess the coverage after CIP terminates. Again, plotting the results for error-free PCP implementation is uses as a reference to show the scale relative to the perfect scenario. Fig. 10 indicates that CIP-Avg requires more node density to achieve full coverage than CIP-Min. Yet, Fig. 11 shows that CIP-Min activates about extra 12% of the network nodes compared to CIP-Avg. Considering both figures concludes that adjusting the coverage range using the average error among the neighbors seems to be the best choice for most cases and one only have be cautious in sparse networks.

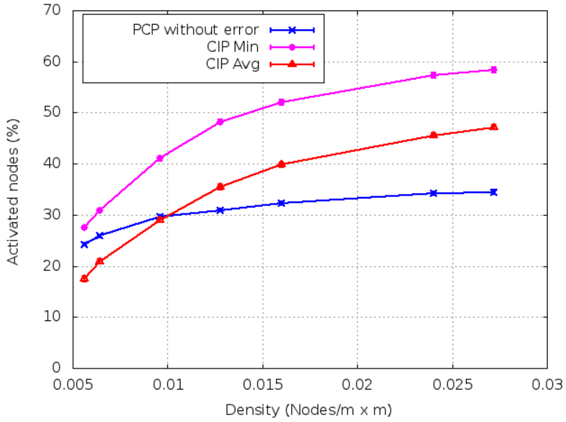


Fig. 11. The percentage of activated nodes for the various node densities when average and minimum errors are factored

VI. CONCLUSION

In this paper we have presented CIP, a distributed coverage protocol mitigating coverage holes caused by inaccurate information of sensors position. The main idea of CIP is to get an accurate bound for the localization error for the individual sensors. This allows sensors to accurately calculate their effective coverage range and enables coverage protocol to engage only necessary sensors in order to ensure full coverage. CIP takes advantages of the underlying area-based localization protocol to support scalability and achieve fast convergence. Basically, anchors form Voronoi diagram based on their communication ranges. The resulting Voronoi cells facilitate clustering the WSN, where the node activation can be scheduled at the level of the cluster and would thus enable the scalability for large networks, avoid the need for clock synchronization among the sensor nodes, and expedite the convergence of the node selection process and the response to changes in the nodes state due to battery depletion and failure. The simulation results have confirmed the effectiveness of CIP under varying levels localization error and demonstrated its performance edge over competing schemes found in the literature.

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