Fine-grained Localization with Pairwise Nodes Coverage

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***Abstract*—Localization is an important design issue in wireless sensor networks. In this paper, we will focus on the sensor deployment for localization with the consideration of coverage and accuracy. Our pairwise localization pattern requires the information of only two coverages for the target. With this information, there are two possibilities of the position. In order to determine the correct location, we design minimum node deployment with regular pattern and an adaptive sequence based localization algorithm (ASL). The proposed ASL algorithm could accurately localize the node in the monitoring area with minimum cost. Also, we extend our results with the noisy model and provide an analysis of the deployment issue. The simulation results show that compared with the traditional triangular and other localization methods, our strategy can achieve the minimum energy, and maximum lifetime.**

***Keywords*-Deployment, localization, pairwise-coverage, scheduling, wireless sensor networks.**

I. Introduction

Wireless sensor networks (WSNs) have received significant attention in literature in recent years. Localization of sensor nodes is an indispensable component for both network operation and sensor data integrity. Among many theoretical problems in sensor network design [1], few research have considered the coverage problem using the least nodes deployed. In this paper, we will give an optimal pairwise coverage problem in wireless sensor networks.

The localization problem from the point of view of coverage and connectivity has been intensely studied in recent years [2]. The K coverage problem is informally defined as a set of sensors such that each point in the given region is covered by at least K distinct sensors [3]. The set of active nodes must also induce a connected communication domain so that they can collectively transmit data to a target node. The deployment of K coverage and K connectivity problems have been intensively investigated in [4], [5].

Previous work in network localization focuses on identifying special graphs that provide efficient localization algorithms. The general idea is to use trilateration graphs [6]. It is either a triangle or a trilateration graph with a trilateration extension, defined as adding an additional vertex with three edges to existing vertices. In iterative trilateration, an initial set of three nodes is fixed and used to define a coordinate system. If the network contains a trilateration graph, one can exhaustively search for the 'seed' triangle in the graph and greedily find the trilateration extensions [7]. Thus, an incremental algorithm can be adopted to find the realization of the network.

A trilateration graph is a stronger condition than global rigidity, and thus may require more edges than necessary to uniquely embed the graph. In this paper, we focus on the localization problem with pairwise information. This means that two possible sensor locations are already known. In this case, there are two possibilities of the unknown position. To obtain the accurate position, we propose an *adaptive sequence localization* algorithm (ASL). In this application, a target moves around a space, following a certain movement pattern (e.g. moving speed). If we know the previous tracking location, we can remove one location using the sample rate and moving speed information. The above process is called *routing pattern*. Our localization method is classified as the fine-grained localization approach. The essential aim of fine-grained localization is to propagate the knowledge of the positions of only a few nodes to the positions of many, using relationships in positions expressed by pairwise distance information [2].

Our deployment strategy meets the requirement that the target should be covered by at least two nodes. Based on this assumption, we provide an optimal node deployment of $K = 2$ coverage. Although many research have been done for general K coverage [4], [5], our approach is unique in that we consider a noisy model. That is, a signal received at a location far away from the center, but still in the transmission radius, is not reliable. The implication is that it is desirable to have some overlap at boundaries of two coverage circles to mitigate the noise factor.

The contributions of this paper are summarized as follows:

- We analyze the one coverage deployment problem, considering the total area is unbounded.
- Using the above analytical results, we provide the minimum node deployment strategy with pairwise coverage. We also extend this strategy to the noise model.
- We propose an adaptive sequence based localization for the target movement and monitoring.
- The simulation results are provided to show the energy consumption using different deployment strategies.

The remainder of the paper is organized as follows: In Section II, we will give a brief review of the related work.

Section III will demonstrate the problem formulation of the system. In Section IV, we will provide the discussion of our minimum node deployment. We will extend our results with the noisy effect of the coverage boundary. Section V presents the sequence based localization algorithm. Then, Section VI will give a discussion of the simulation results. This paper will conclude in Section VII.

II. Related Work

The coverage problem for localization in wireless sensor networks has been intensively studied in recent years. Most of these works study the problem of covering every point in the sensing field with sensing disks [8] or detecting a target when it passes through the sensing field [9].

In [10], Wu and Yang focused on area coverage with random sensor deployment. They propose two novel node scheduling models with adjustable sensing ranges, as opposed to the traditional uniform sensing range node scheduling method. In [11], Lu and Wu studied the maximization of WSN lifetime while maintaining both discrete target coverage and network connectivity.

Several optimal deployment patterns have been studied to achieve K connectivity and/or K coverage in WSNs in [4], [3], [12]. The optimality of some patterns is proved under regularity constraints.

In [13], Wang and Tseng consider the K coverage placement problem and distributed dispatch problem. The proposed solutions allow an arbitrary relationship of sensors' communication distance and their sensing distance, and can work properly under both binary and probabilistic sensing models.

The most recent work with the sequence based localization is shown in [14]. Zong *et al*. proposed a robust tracking framework using node sequences, an ordered list extracted from unreliable sensor readings. Instead of estimating each position point separately in a movement trace, they convert the original tracking problem to the problem of finding the shortest path in a graph, which is equivalent to optimal matching of a series of node sequences.

In this paper, we provide a class of simple algorithms referred to as sequence based localization, which require the information of the pairwise distances. This means the target is covered by at least two sensor nodes. In this way, we can get the accurate position according to the movement pattern. Note that our localization method is much simpler compared to existing localization algorithms. However, this simplified model retains the basic ideas of range based localization, while at the same time revealing key insights and relationships between the coverage and localization.

III. Problem Formulation

We assume that the WSN is running a target tracking application. The objective of the network is to provide accurate location information of the target.

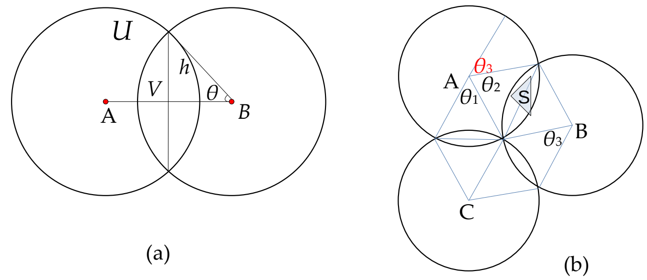

Figure 1. Solution of one coverage problem.

Suppose that there are two groups of nodes in this area. Each group of nodes will provide one piece of coverage deployment. We assume that the coordinates of sensors are known, and the location of the target is estimated based on the measurements and coordinates of nearby sensors. We first define the requirement of our solution:

(1) All the deployed nodes must have the same transmission range.

(2) The target node entering the monitoring area can only obtain the information of the distance within its own range.

(3) The target node has no knowledge of the direction information.

We then will discuss the deployment strategy with minimum number of nodes.

IV. Minimum nodes deployment

We define the network area S. Then, we will discuss the minimum number of the nodes for one coverage problem, which can guarantee one coverage for each point in S. The transmission range of each node is set to r. The overlapped area is the set to S'.

To provide the solution for the one coverage problem, we will first discuss the overlap problem with one coverage and find the minimum overlap of them. We then offer several definitions accordingly: $A \cap B = V_{AB}$ means that the area V is the overlapped area between node A and node B. $A \cup B = U_{AB}$ means that the area U is the overall area covered by node A and node B.

We need all the overlapped area to completely cover S. Suppose that there are n sensor nodes in the monitoring area. $s_1, s_2, \ldots, s_n$ represent the coverage of each node.

To express the total coverage in this area, we give the equation as follows:

$$C = \left| \begin{array}{cccc} s_1 & s_2 & \ldots & s_n \end{array} \right| \quad (1)$$

Then, the total area should be: $U_1 = s_1 \cup s_2 \cup \ldots \cup s_n$.

Figure 1b shows the typical deployment when U_1 completely covers area S. Then, we consider the overlapped problem: $s_i \cap s_j = V_{ij} + V_{ji}$.

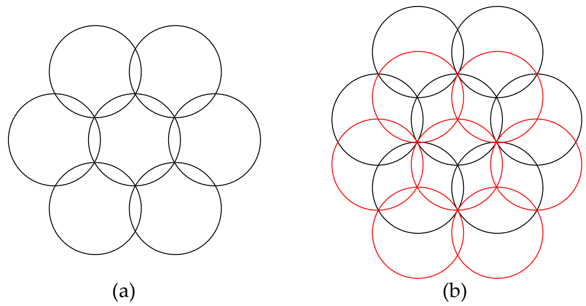

Figure 2. Deployment with pairwise nodes coverage.

$$C_1 = \begin{vmatrix} 0 & V_{1,2} & V_{1,3} & \dots & V_{1,n} \\ V_{2,1} & 0 & V_{2,3} & \dots & V_{2,n} \\ V_{i,1} & \dots & \dots & \dots & \dots \\ V_{n-1,1} & V_{n-1,2} & V_{n-1,3} & \dots & V_{n-1,n} \\ V_{n,1} & V_{n,2} & V_{n,3} & \dots & 0 \end{vmatrix} \quad (2)$$

We consider the cases: $S \subset V$, then node A and node B can cover the area completely.

As shown in Figure 1a, with the transmission range r, the overlapped area $V_{i,j}$ of node i and node j can be calculated as follows:

$$V_{i,j} = \theta_{i,j} \times r^2 - d_{i,j} \times h(i,j),$$

where $h(i,j)$ is the half height of $V_{i,j}$, and $d_{i,j}$ is the distance of node i and node j. The $\theta_{i,j}$ is the arcs shown in Figure 1a.

This equation could be reverted into the following format:

$$V_{i,j} = \theta_{i,j} \times r^2 - r^2 \times \sin(2\theta_{i,j}) \quad (3)$$

Suppose that there are n nodes within the transmission range of node i. Then, we have:

$$\Sigma_{j=1}^{n} \theta_{i,j} = 2 \times \pi \quad (4)$$

Then, we have the objective function to achieve full coverage and minimum overlapping in the area:

$$\begin{aligned} \min \Sigma_{j=1}^{n} V_{i,j} \\ s.t. \Sigma_{j=1}^{n} \theta_{i,j} = 2 \times \pi \\ d_{i,j} \leq 2 * r \\ d_{i,j} \geq r \end{aligned} \quad (5)$$

To solve the ILP problem, we will first discuss Figure 1b. Since $\theta_1 + \theta_2 + \theta_3 = \pi$, only when $\theta_1 = \theta_2 = \theta_3 = \pi/3$, the size of the overlapped area is the smallest. Figure 2a is the solution. According to the above solution, we can get the result below:

$$V_{i,j} = \pi r^2/6 - \sqrt{3}/4 \times r^2 = 0.09r^2 \quad (6)$$

with $d_{i,j} = \sqrt{3}r$ and $\theta_{i,j} = \pi/6$.

Then, for each node, the minimum overlapped area is $0.086 \times \pi r^2$. Next, we will move the above problem to pairwise coverage deployment. The pairwise coverage problem is that each node in this area is covered by two monitoring nodes. When a target enters into this area, it will be covered by at least two nodes. We use $V_{i,j}$ and $V_{i,j}^{'}$ for the overlap area of C_1 and C_2, respectively. According to the above definition, we then have the following equation:

$$\begin{aligned} C_3 =& C_1 \cap C_2 \\ =& \begin{vmatrix} 0 & V_{1,2} & \dots & V_{1,n} \\ V_{2,1} & 0 & \dots & V_{2,n} \\ \dots & \dots & 0 & \dots \\ V_{n,1} & V_{n,2} & \dots & 0 \end{vmatrix} \times \begin{vmatrix} 0 & V_{1,2}^{'} & \dots & V_{1,n}^{'} \\ V_{2,1}^{'} & 0 & \dots & V_{2,n}^{'} \\ \dots & \dots & 0 & \dots \\ V_{n,1}^{'} & V_{n,2}^{'} & \dots & 0 \end{vmatrix} \end{aligned} \quad (7)$$

We argue that $C_3 = \emptyset$. This means the overlapped area has no contribution to the other coverage. Even if it does, the largest equilateral triangle within the overlapped area is the s in Figure 1b. The size of s is as small as $0.018 \times \pi r^2$. However, in our system, we do not apply the small change. We will adopt the overlapped area for noisy control, and address this problem in the following section.

Then, the objective function is defined as follows:

$$\begin{aligned} \min(\Sigma_{k=1}^{n} V_{i,k}), (\Sigma_{k=1}^{n} V_{i,k}^{'}) \\ s.t. \Sigma_{k=1}^{n} \theta_{i,k} = 2 \times \pi \\ d_{i,k} \leq 2 \times r \\ d_{i,k} \geq r \end{aligned} \quad (8)$$

Figure 2b shows the solution for the the pairwise coverage deployment according to the above discussion. The position of the two groups could be variable when none of them are a superposition of each other. Based on this deployment, we will offer the extension for the noisy model and adaptive sequence based localization in the next sections.

V. Deployment with Noise Model

In [15], Wang *et al.* discussed the coverage problem with the noise model. The proposed model discussed the coverage issue from another point of view. Due to the existence of noise, the distance estimation will be distributed within a certain range around the true distance. The true distance between the sensor and target will fall in the range. When the true distance between sensor i and the target t is $d_{i,t}$, we assume the estimated distance $d_{i,t}^{'}$ by sensor i will fall in the range $[d_{i,t} - e, d_{i,t} + e]$ with high probability. e is the error bound:

$$d_{i,t} - e < d_{i,t}^{'} < d_{i,t} + e$$

The multiple coverage (> 2) in the noisy region is not just desirable, it is necessary to incorporate the noisy model into our deployment issues. Note that our deployment is with the consideration of noise at the boundary of a coverage circle. This part will consist of two cases, as shown in Figure 3.

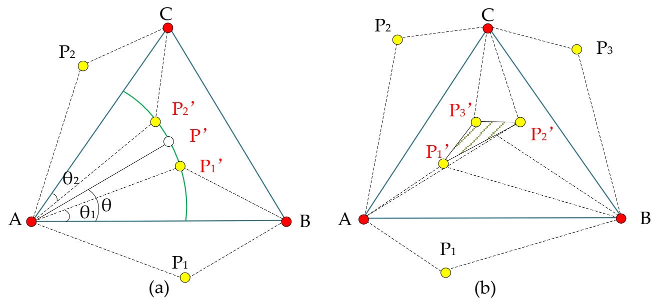

Figure 3. Boundary effect with two cases.

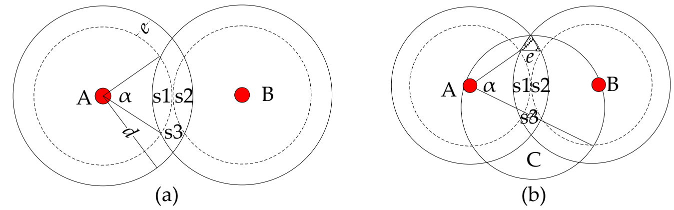

Figure 4. Deployment with boundary effect.

When the target is covered by three nodes, then two of them is within the boundary range, and the remaining one is in the real range. As shown in Figure 3, suppose P_1 is within the real range, P_2 and P_3 is at the boundary. $d_{p_1,a}$ is the distance between A and P_1, and $d_{p_1,b}$ is the distance between B and P_1. The position of P_1 could be expresses as $p(\theta, d_{p_1,a}, \overline{AB})$. This means that the real position must be on the circle with the radius of $d_{p_1,a}$. We need to obtain the θ for the real position P', as shown in Figure 3a. The arc obtained from the sensor A could be represented as follows:

$$\theta_1 = argcos\frac{d_{a,b}^2 + d_{p_1,a}^2 - d_{p_1,b}^2}{2d_{a,b}d_{p_1,a}}$$

If θ_a is the angle of AC and AB, as shown in Figure 3a, then

$$\Delta\theta = \theta_a - \theta_1 - \theta_2. \tag{9}$$

In our system, we set the position $p(\theta_1 + \frac{1}{2}\Delta\theta, d_{p_1,a}, \overline{AB})$, with the average angle between p_1' and p_2' being the preferred position.

In the other case shown in Figure 3b, the target is in the boundary area of the three nodes A, B, and C. We then redefine the three nodes with positions $\{x_0', y_0'\}$, $\{x_1', y_1'\}$, and $\{x_2', y_2'\}$. Then, the centroid node of the area is the selected position in this area. We can obtain the position according to the centroid point $g(p_0, p_1, p_2) = \{g_x, g_y\}$.

$$g_x = \frac{1}{6\Delta s}\sum_{i=0}^{2}(x_i' + x_{i+1}')(x_i'y_{i+1}' - x_{i+1}'y_i') \tag{10}$$

$$g_y = \frac{1}{6\Delta s}\sum_{i=0}^{2}(y_i' + y_{i+1}')(x_i'y_{i+1}' - x_{i+1}'y_i') \tag{11}$$

The resolution is defined in WSNs as the smallest change it can detect in the quantity that it is measuring. In our model, the distance of the two or the area of three possible positions is defined as the resolution in our deployment.

Theorem 1: Considering the deployment with the above strategy, the overlapped area could be covered by a maximum of three nodes with a resolution of $e \times \sqrt{3}$.

Proof: The pairwise coverage problem has been investigated in the above section. However, we have not adopted the noise model in that discussion. To cover all of the coverage boundary area, we need to move the surrounded sensors closer to the current one. The maximum length of the movement is the range of the boundary e.

In this case, the resolution of the possible detected positions is in the area $s1$, $s2$, or $s3$. If this target is in area $s1$, then the distance measured by A is within the real range, and the distance from B is in the boundary area. Then, we will use the method from Figure 3a. If the target is in area $s3$, then, both of the measurements are in the boundary area. In this case, we will use the method shown in Figure 3b.

For $s1$ and $s2$, as shown in Figure 4, if we move this two area for pairwise nodes, both of $s1$ and $s2$ are in two real range coverage by the sensors A and C. Only $s3$ is considered as the area for the noisy model. So, the overlapped area could be covered by a maximum of 3 nodes with a resolution of $e \times \sqrt{3}$, as shown in Figure 4b according to our deployment strategy. To obtain the size of area $s3$, we use the following functions:

$$\begin{aligned} s &= \int_{(r-e)(1-\frac{\sqrt{3}}{2})}^{r-e} 2\pi x dx - (\frac{\pi}{12} - \frac{\sqrt{3}}{8})(r-e)^2 \\ &= \pi(r-e)^2(\sqrt{3} - \frac{5}{6}) + \frac{\sqrt{3}}{8} \times (r-e)^2 \end{aligned} \tag{12}$$

■

Based on the above discussion, we propose our adaptive sequence based localization method.

VI. Adaptive Sequence Based Localization

In this section, we will present a sequence based algorithm to obtain the position accurately in this monitoring area S. All of the nodes in this area have their own label, as shown in Figure 5. Basically, the located node is covered by two sensor nodes, in other words, we can obtain the two distances d_1 and d_2. With this information, we can get the two probable positions, as shown in Figure 5a. There are two possible locations, c or c', for the target. However, in some special cases, when the node enters the boundary area, it is covered by at least three nodes. Then, in this case, we can get the position and definitely remove the other probability.

In Figure 5a, if the positions, p_A and p_B, of A and B, and the distances, l_A and l_B, from A and B, are known, there are two possibilities of the position C, say $f(l_A, l_B, p_A, p_B)$

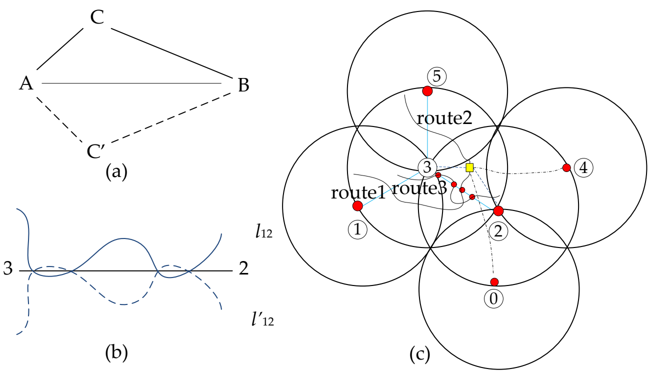

Figure 5. Adaptive sequence based localization.

and $f'(l_A, l_B, p_A, p_B)$. We need to remove one possibility and get the real position r_c.

From Figure 5c, we offer three patterns of the route type:

(1) Previous track: This method will remove the node position regarding the information of the previous track.

(2) Future track: This means the system could not make a decision, has to store the current path ($inc(c)$), and remove it after some time.

(3) Remove across the border: This could be the pattern shown in Figure 5b. If the target node follows this type of route and always crosses over the boundary, it will be difficult to remove the other route according to patterns (1) and (2). In this situation, since node 2 and node 3 can communicate with each other, we will require the two nodes to send two messages to these two areas. If one of them could be received by the target, it then removes the other possibility. These two messages will be sent to the target when the target crosses the border.

The algorithm below offers the detailed process of our localization method in Algorithm 1.

VII. Performance Evaluation

A. Simulation Analysis

Distance related measurements are dependent on a received signal strength indicator. This is a common technique used in the distance estimation. It has no additional hardware requirements, and a distance computation is based on the simple Friis equation [16]:

$$e^R(d) = \frac{e^T G_t G_r \lambda^2}{4r^2 d^2},$$

where $e^R(d)$ is the received power in dependence on the distance between transmitter and receiver, e^T is the transmitted power. G_t, G_r are the transmitter's responses, and receiver's antenna gain. λ is the wavelength of transmitted signal in meters.

The energy consumption per unit of the information transmission is assumed to be:

$$e^t_{i,j} = e^T + \epsilon_{amp} d^4_{i,j},\ e^r_{i,j} = e^R,$$

Algorithm 1 Adaptive sequence based localization (ASL)

$sequencelist$: the sequence list for the the temp possibilities

A target node enters into the monitoring area.
if $getSensorNodes() = 2$ **then**
  store $f(l_i, l_j, p_i, p_j)$ and $f'(l_i, l_j, p_i, p_j)$
  add p_i, p_j to $sequencelist.$
  if $l_i + l_j = radius$ **then**
    add crossover flag $l_{i,j}$ to $sequencelist.$
    send "remove request to node i and j" to $\min(l_i, l_j)$.
    broadcast "remove response" to subarea $v_{i,j}$.
  end if
end if
if $getSensorNodes() = 3$ **then**
  while not visited all of the $sequencelist$ **do**
    remove according to previous track.
    $inc(c)$
    get $r_c = g(p_i, p_j, p_k)$ (equation 10 and 11).
  end while
end if
if $getSensorNodes() = 4, l_i = l_j = l_k = l_m = r$ **then**
  while not visited all of the $sequencelist$ **do**
    remove according to future path pattern.
    $inc(c)$
    get $r_c = g(p_i, p_j, p_k)$ (equation 10 and 11).
  end while
end if

where e^t and e^r are the energy consumed in the transceiver circuitry at the transmitter and the receiver, respectively. ϵ_{amp} is the energy consumed at the output transmitter antenna for transmitting one meter. The receiver circuitry is, in general, more complex and consumes more energy than the transmitter circuitry within the same order of magnitude [17]. On a wireless sensor node, energy is expended through transmitting (E_{Tx}), receiving (E_{Rx}), processing (E_P), and sensing (E_S). Assuming there is no sensing during localization, an estimate of the total energy (E_T) consumed is $E_T = E_{Tx} + E_{Rx} + E_P$, where

$$E_{Tx} = \sum_{i=0}^{n}\sum_{j=0}^{n} e^t_{i,j},\ E_{Rx} = \sum_{i=0}^{n}\sum_{j=0}^{n} e^r_{i,j},$$

In our simulation, residual energy levels are updated and the shortest cost path computation is completed within the routing information update interval. The energy consumed in the communication of routing control packets and in the shortest cost path computation is ignored in the simulation.

We will first simulate the case of pairwise coverage compared with triangular coverage. Note that both of them based on the range-based method. However, the energy

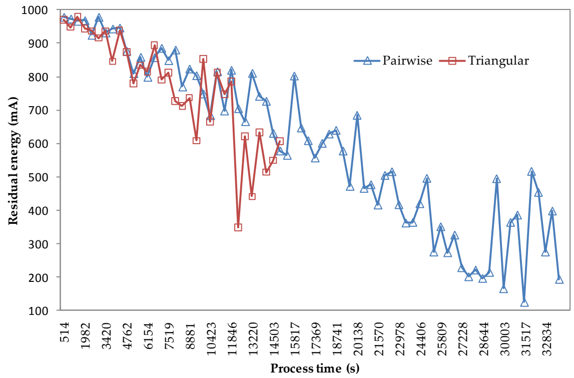

Figure 6. Comparison of residual energy with different methods.

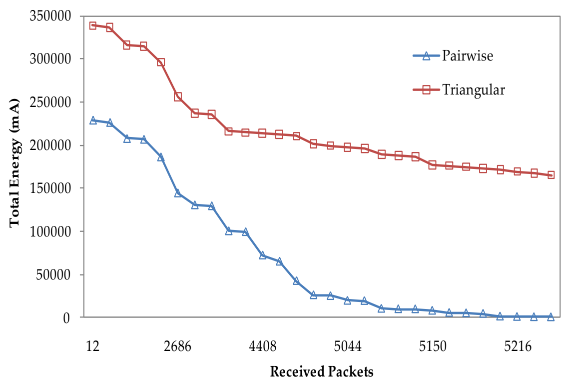

Figure 7. Comparison of total energy with different methods.

consumption of the two are different. For the three coverage problem, more energy is consumed since more nodes are needed for the range-based test. In this case, we don't need the consumption for the communication. Then, for a sensor node i, we use the following expression $e_2(i)$ and $e_3(i)$ for the energy consumption of pairwise coverage and triangular coverage, respectively:

$$e_2(i) = (E_P + E_{Tx} + E_{Rx}) \times num_{packets} \tag{13}$$

$$e_3(i) = E_P \times num_{packets}, \tag{14}$$

where $num_{packets}$ is the number of packets for transmission.

B. Simulation Results

We use SensorSim [18] for our evaluation. We set the network size to 210 and 340 nodes separately for pairwise and trilateration deployment in this simulation. Each node is within a radius of $30m$, and has a sensor cost of $20mA$. The transmission range of the sensor node is $40m$. And the transmit cost and receive cost is $150mA$ and $15mA$. The nodes are deployed in a 460×300 area. For triangular coverage, according to our deployment strategy, it will need 310 nodes to guarantee full coverage of the area.

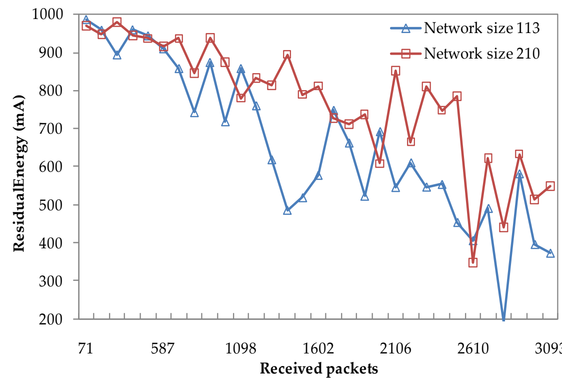

Figure 8. Comparison of residual energy with different network sizes.

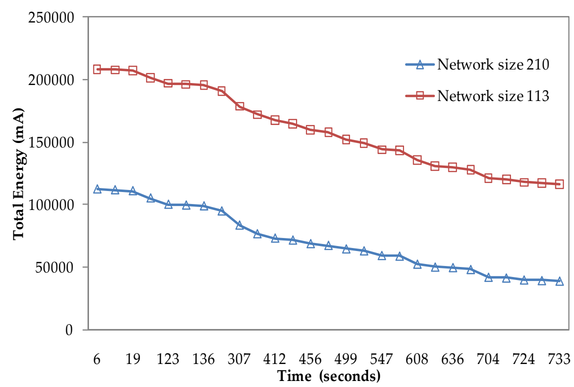

Figure 9. Comparison of total energy with different network sizes.

In Figure 6, we can see the simulation results of the residual energy with different methods. The simulation has stopped after one node has died. The simulation results show that each node in pairwise deployment consumed more energy than the nodes in the triangular coverage. Therefore, the lifetime of two coverage is shorter than triangular coverage. From Figure 7, we know that the total energy consumption rate of pairwise coverage is slower than triangular coverage.

Figures 8 and 9 provide the results with different network sizes. The simulation results show that with the same number of received packets by the network area, the energy is consumed larger with the larger network size. This means the energy consumption of the transmission is more than that of the range measurement. In Figure 10, the results show that with a different deployment strategy, the lifetime of pairwise deployment is better than the triangular one. For each point area, when the nodes are in the range of the three nodes, it will consume more energy than the node that is covered by the two nodes.

From the above simulation results, we can see that with the same number of nodes, the energy consumption of the pairwise coverage is less than the deployment with

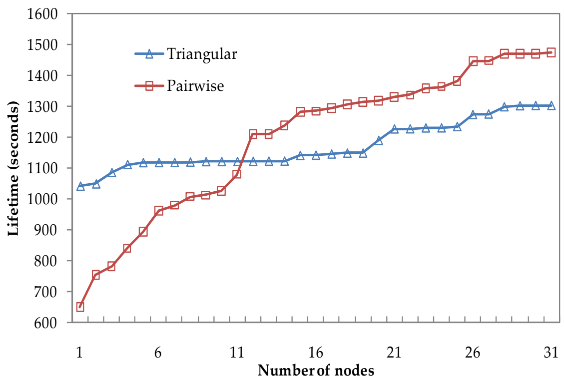

Figure 10. Comparison of node lifetime with different methods.

triangular coverage. The pairwise coverage deployment, in turn, increases the life time of networks.

VIII. Conclusion

In this paper, we proposed an ASL localization algorithm, which is based on the assumption of the minimum pairwise coverage deployment. We first study the one minimum coverage problem with the regular pattern, and then extend it to the two coverage deployment. We also apply our strategy to the noisy model and give an analysis of the boundary area. The simulation results show that with our deployment strategy and localization, the total energy consumption is lower than the traditional triangular coverage. The lifetime of pairwise deployment is also better than the triangular coverage within the same area.

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