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Maximizing Sensor Reuse Based on New Geometric Concepts

GUANGBIN FAN AND JINGYUAN ZHANG*
Department of Computer and Information Science
University of Mississippi
University, MS 38677, U.S.A.
E-mail: gfan@cs.olemiss.edu
**Department of Computer Science*
University of Alabama
Tuscaloosa, AL 35487, U.S.A.
E-mail: zhang@cs.ua.edu

A wireless sensor network is composed of a distributed collection of nodes which corporate in performing sensing, computation and communication tasks. Since sensor nodes operate on battery power, their communication range will decline as time passes. When the energy of the sensor nodes has declined to a level that they cannot communicate with each other, the network cannot be sustained and might be replaced by a new sensor network. However, the old sensors may have a lot of valuable data, and it is wise to retrieve as much information as possible from the old sensors. The maximum sensor reuse problem concerns deploying the new sensor network to maximize the number of old sensors that can communicate with the sensors in the newly deployed network. This paper proposes two new geometric concepts, network distance and network bisector, and uses them to solve the maximum sensor reuse problem. Specifically, the maximum sensor reuse problem can be solved in O(n^2 log n) time if n existing sensors are to be considered.

Keywords: sensor networks, sensor reuse, optimization, network distance, network bisector, computational geometry

1. INTRODUCTION

A wireless sensor network is a class of ad-hoc networks [6]. The nodes in sensor networks are relatively static, and can coordinate among themselves to perform large sensing, computing, and communication tasks [4]. Wireless sensor networks are attractive because they can be deployed in nearly any kind of environment without wired connections. They are essential in the battle field and hazard environments. Deployment and coverage problems are important topics in the wireless network and they affect nearly every aspect of the network, such as topology, power consumption, routing, and QoS issues [7, 9, 13].

Since sensor nodes operate on battery power, their communication range will decline as time passes [1, 10]. When the energy of the sensor nodes has declined to a level that they cannot sustain the communication with each other, the network is dead. Normally, there are two kinds of methods that can be used to deal with a dead network. One

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is to add new sensors from time to time to keep the network connected. The other is to deploy a completely new network to replace the old one. In this paper, the second method, i.e., the deployment of a new sensor network, is assumed. Although the old sensor network is dead, the old sensors may still have a certain communication range and have some valuable data. Instead of totally deserting the old sensors, it is wise to deploy the new sensor network that can retrieve the maximum amount of information from the old sensors.

A sensor network can be randomly deployed or regularly deployed [5, 14]. To deploy the sensors based on a regular geometric topology, a precision weapon can be used to place a sensor very close to its planned location. The author in [2] discussed three basic types of coverage, one of which is a blanket coverage. A blanket coverage is able to achieve a static arrangement of elements that maximizes the detection rate of targets appearing within the coverage area. In this paper, we will consider the blanket coverage with a regular geometric structure. Specifically, the honeycomb configuration is used because it is able to cover an area with the minimum number of sensors. Given a fixed number of sensors with a common transmission radius, placing the sensors on a triangular lattice can cover an area with the smallest possible sensor density [11]. In the triangular lattice, the coverage of each sensor is hexagonal. This configuration is also known as the honeycomb configuration [12]. Although it is costly to deploy a regular structure of sensors, simpler and more efficient communication algorithms are readily available [8] and a regular structure will benefit many applications such as sensor-based weather forecasting.

The old sensor network may not necessarily have the same topology as the new one [5]. Although the old network might be planned in a regular manner, some obstacles, such as a river, prevent sensors from actually being placed at the planned locations. The network can be planned to be uniform, but the actual network may not be so.

In this paper, we will study how to deploy a new sensor network with a honeycomb configuration that is able to reuse (specifically, to communicate with) as many old sensors as possible. After the new sensor network is deployed, it may be the case that not all of the old sensors will have a nearby new sensor to communicate with because the old sensors only have a limited range of communication. This limited range of communication can arise in many different ways. For one thing, the network can be monitored, and when the network becomes partitioned, the communication ability can be estimated. An alternative is to ask sensors to periodically send in their current transmission range. The problem here is how to deploy the new sensor network so that the maximum number of old sensors can be reused. The problem will be referred to as *the maximum sensor reuse problem*.

To solve the problem, we propose two new geometric concepts: *network distance* and *network bisector*. Different from the general Euclidian distance, the network distance between two points describes the distance from one point to the network derived from the other point. The *network bisector* between two points is an extension of the perpendicular bisector of two points. We also use circular arcs to model the bounded network bisector and so solve the maximum sensor reuse problem efficiently. Specifically, the maximum sensor reuse problem can be solved in $O(n^2 \log n)$ time if n existing sensors are to be considered. To the best of our knowledge, it is the first time such a result has been reported in the literature.

The remainder of this paper is organized as follows. Section 2 proposes the network distance concept and defines the network bisector. Section 3 shows how to solve the maximum sensor reuse problem through the network bisector. Section 4 presents the algorithm and analyzes the time complexity. Finally, section 5 summarizes the results.

2. NETWORK DISTANCE AND NETWORK BISECTOR

In this section we will first propose a new distance metric, *network distance*. The network distance between two points describes the distance from one point to the network derived from the other point. Then we will study the network bisector between two points based on the network distance.

As mentioned earlier, a blanket coverage using the minimum number of sensors is exactly a honeycomb network [12], which consists of hexagonally shaped cells with the same size and orientation. The sensors are placed at the cell centers of the honeycomb network. A honeycomb network is completely determined by one hexagon because, once one hexagon is known, the remaining hexagons can be easily derived. As shown in Fig. 1, if the center hexagon is fixed, the whole network is fixed. In the following discussion, we assume the network has a fixed cell size and network orientation. A network with a fixed cell size and network orientation is solely determined by the position of one cell. If the position of one cell center is C, we call that network the *spreading network* of C, which is defined as follows.

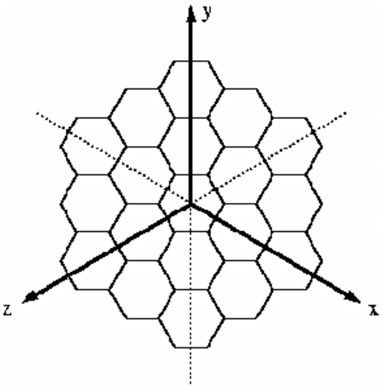


Fig. 1. Honeycomb network spread by a point.

Definition 2.1 Given a position C and a shiftable sensor network T with a fixed cell size and network orientation, the network T spreading from C, $T(C)$, is the network with C being one of its cell centers. $T(C)$ is called a *spreading network* of C, and C is called a *starting point* of $T(C)$.

Next we define the network distance between a point and a network, followed by the definition of the network distance between two points under network pattern T.

Definition 2.2 The *network distance* between a point P and a network T, denoted by $nd(P, T)$, is defined as the distance between P and the closest cell center in T.

Definition 2.3 The *network distance* from a point P to another point Q under network pattern T, denoted by $nd_T(P, Q)$, is defined as the distance between P and $T(Q)$, i.e. the network spread from Q. When no confusion arises, we will omit the subscript T in $nd_T(P, Q)$.

It is obvious that if P is located within a cell with its center at C in the network $T(Q)$, the network distance between P and Q, $nd(P, Q)$, is the distance between P and C as shown in Fig. 2.

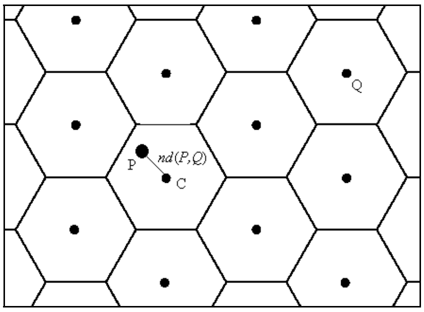


Fig. 2. Network distance between P and Q.

The network distance between two points is commutative. It is easy to verify that the network distance from P to Q equals the network distance from Q to P. As shown in Fig. 3, $nd_T(P, Q) = |PQ'| = |QP'| = nd_T(Q, P)$.

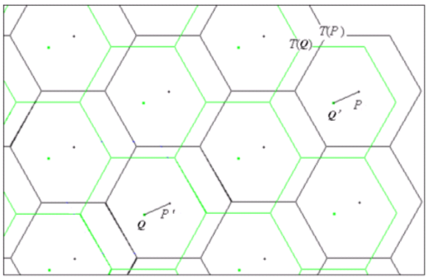


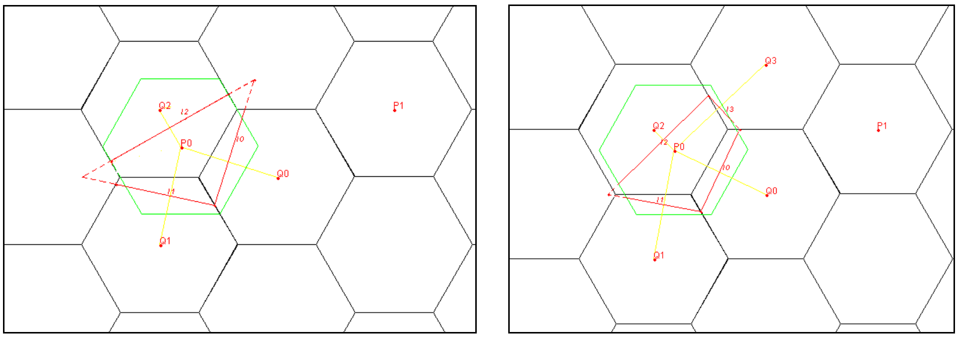
Fig. 3. Commutative property of the network distance.

In geometry, we use Euclidian distance to define the perpendicular bisector of two points. The perpendicular bisector of two points is a locus of points whose Euclidian distances to these two points are equal. We will use the network distance to define the network bisector of two points as follows.

Definition 2.4 The *network bisector* between two points P and Q under network pattern T is denoted by $B_T(P, Q)$ and is defined as the locus of points x such that the network distance between P and x is the same as the network distance between Q and x. When no confusion arises, we will omit the subscript T in $B_T(P, Q)$.

Next we will show how to compute the network bisector between two points P_0 and P_1. Due to the spreading property of a honeycomb network, any point on the plane can be mapped to a point within $H(P_0)$ which is the hexagonal cell centered at P_0. Therefore, it is sufficient to use the $H(P_0)$ to compute the locus instead of the whole plane.

Next we study the relationship between $nd(P_0, x)$ and $nd(P_1, x)$ for a given point x within $H(P_0)$. Again, by the spreading property of the honeycomb network, it is not hard to figure out that we can use any center in the spreading network $T(P_1)$ instead of P_1. $H(P_0)$ will intersect with either three or four cells of $T(P_1)$ as shown in Fig. 4. We assume $H(P_0)$ is not identical to any cell of the network $T(P_1)$. If they are identical, it is obvious that the locus will be the whole plane. Now let us consider the case in which $H(P_0)$ intersects with four cells in $T(P_1)$ as shown in Fig. 4 (b), with the three-intersection case being similar. Assume the four cells that intersect $H(P_0)$ are centered at Q_1, Q_2, Q_3, and Q_4. $H(P_0)$ is divided into four parts, each of which is an intersection of $H(P_0)$ and a cell in $T(P_1)$, represented by $I_i = H(P_0) \cap H(Q_i)$, $i = 1 .. 4$. Each part has the following property.



(a) (b)

Fig. 4. Computing the network bisector of P_0 and P_1.

Lemma 2.1 Assume P_0 and P_1 are two points, and Q_i is a cell center of the network spread by P_1, i.e., $T(P_1)$. For any point O, $nd(P_0, O) = |OP_0|$ and $nd(P_1, O) = |OQ_i|$ if and only if $O \in I_i = H(P_0) \cap H(Q_i)$.

Proof: Suppose $O \in I_i = H(P_0) \cap H(Q_i)$, that is, $O \in H(P_0)$ and $O \in H(Q_i)$. $O \in H(P_0)$ implies $P_0 \in H(O)$ and $O \in H(Q_i)$ implies $Q_i \in H(O)$. Therefore, $nd(P_0, O) = |OP_0|$ and $nd(P_1, O) = nd(Q_i, O) = |OQ_i|$. On the other hand, suppose $nd(P_0, O) = |OP_0|$ and $nd(P_1, O) = |OQ_i|$, then $P_0 \in H(O)$, and $Q_i \in H(O)$. Therefore $O \in H(P_0) \cap H(Q_i) = I_i$. ❑

In $I_i = H(P_0) \cap H(Q_i)$, $i = 1 .. 4$, construct the perpendicular bisector l_i between P_0 and Q_i, as shown in Fig. 4. According to Lemma 2.1, it is easy to see that: (1) if O is on line segment l_i, then $nd(P_0, O) = nd(P_1, O)$; (2) if O is on the side that is closer to P_0, then $nd(P_0, O) < nd(P_1, O)$; (3) and if O is on the side that is closer to P_1, then $nd(P_0, O) > nd(P_1, O)$. All bisector line segments l_i (or their extensions) will form a polygon. If $H(P_0)$ intersects four cells in $T(P_1)$, the polygon will be a quadrilateral. (Note that if P_0 intersects with three cells in $T(P_1)$, the polygon will be a triangle.)

Denoting this polygon by $L(P_0, P_1)$, we have the following property. The part of $L(P_0, P_1)$ within $H(P_0)$ is exactly a complete representation of all the bisector line segments l_i within $H(P_0)$. Assume that I_i and I_{i+1} are neighboring areas in $H(P_0)$, where $I_i = H(P_0) \cap H(Q_i)$ and $I_{i+1} = H(P_0) \cap H(Q_{i+1})$. Suppose l_i is the perpendicular bisector between Q_i and P_0, and l_{i+1} is the perpendicular bisector between Q_{i+1} and P_0. Assume that I_i and I_{i+1} have a common edge M which is on the cell edge of $H(Q_i)$ and $H(Q_{i+1})$. It is not difficult to see that M is the perpendicular bisector of Q_i and Q_{i+1}. L_i, L_{i+1} and M must be coincident at one point because they are the three perpendicular bisectors of the triangle $\Delta\, Q_i\, Q_{i+1}\, P_0$. Therefore, the part of $L(P_0, P_1)$ inside $H(P_0)$ is a complete representation of all bisector line segments inside $H(P_0)$. According to Lemma 2.1, the part of contour $L(P_0, P_1)$ within $H(P_0)$ is the locus of the starting points O in $H(P_0)$ such that the network distance $nd(P_0, O) = nd(P_1, O)$. Therefore, we have the following theorem.

Theorem 2.2 The part of $L(P_0, P_1)$ within $H(P_0)$ is the locus of all the points O in $H(P_0)$ such that the network distance $nd(P_0, O) = nd(P_1, O)$, i.e. the network bisector, $B(P_0, P_1)$, within $H(P_0)$. ❑

Fig. 5 illustrates of the network bisector between P_0 and P_1 on the whole plane.

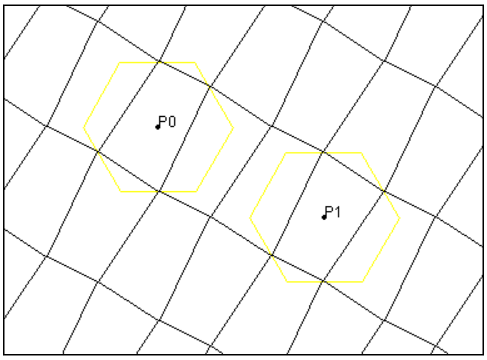


Fig. 5. The network bisector between P_0 and P_1.

3. SOLUTION TO THE MAXIMUM SENSOR REUSE PROBLEM

In this section we will use the proposed network bisector to solve the maximum sensor reuse problem. When we deploy a new sensor network, we assume that the old sensors may not be uniformly distributed either because they have a different configuration from the new one, or they are arbitrarily distributed initially. If a new sensor is placed within the limited communication bound of an old sensor, the old sensor can communicate with the new one in both directions. Then the information stored in the old sensor can be retrieved. Our goal is to deploy the sensor network such that the maximum number of old sensors can communicate with the new sensors.

Given a new sensor network *T* with a fixed cell size and network orientation, the deployment is to find the position *C* for one of its cell centers. Consider the network distance between an old sensor *P* and the position *C* under the network pattern *T*. If the network distance is smaller than the communication range of the old sensor, there exists a new sensor in the new network that is within the communication range of the old sensor. Therefore, the information of the old sensor can be reused (retrieved to be exact). Otherwise, the old sensor cannot be reused. For example, given a sensor network *T* deployed at *C*, and the given communication range (also called bound in this paper) of the old sensor as shown in Fig. 6, only P_0, P_2 and P_7 can be reused under this network deployment.

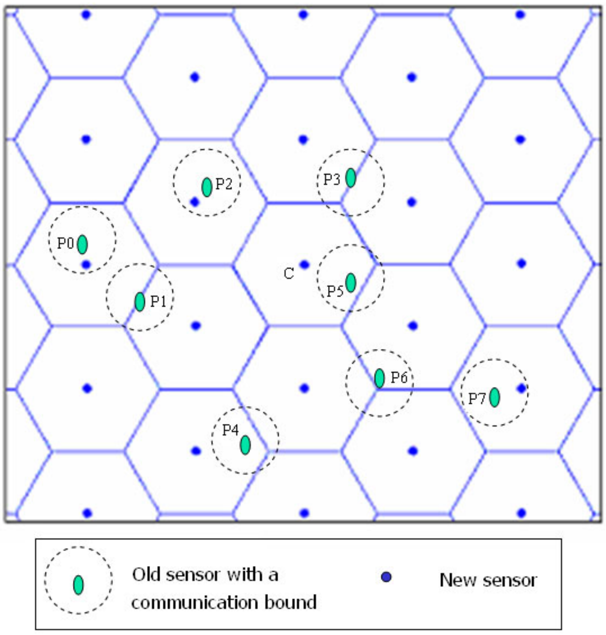


Fig. 6. The sensor reuse example.

Our goal is to maximize the number of old sensors that can be reused. Here we give the definition of the maximum sensor reuse problem.

Definition 3.1 Given a set *S* of *n* arbitrarily distributed old sensors, $S = \{P_0, P_1, \ldots, P_{n-1}\}$, with communication bound $|R|$, and a movable blanket coverage sensor network with a fixed sensor radius and network orientation, the *maximum sensor reuse* problem is to find the sensor network deployment point *C* that maximizes the number of old sensors with their network distances, $nd(P_i, C)$, within the communication bound $|R|$.

Next we present our solution to the problem of maximum sensor reuse. For each sensor P_i, we will show how to get the bounded network bisector that will be used to solve the conditional maximum sensor reuse problem under the condition that P_i has the largest network distance to the network. The maximum number of sensors that can be reused can be found by combining conditional optimal solutions.

As mentioned in the previous section, network bisector $B(P_0, P_1)$ represents the locus of all starting points x such that $nd(P_0, x) = nd(P_1, x)$. We will consider $B(P_0, P_1)$ within $H(P_0)$. Recall that the contour $L(P_0, P_1)$ is a superset of $B(P_0, P_1)$ within $H(P_0)$, but we do not distinguish between $L(P_0, P_1)$ and $B(P_0, P_1)$ within $H(P_0)$ in the following discussion. If a point y is within $L(P_0, P_1)$, then $nd(P_0, y) < nd(P_1, y)$; if y is outside $L(P_0, P_1)$, then $nd(P_0, y) > nd(P_1, y)$. Now we will show how to incorporate the communication bound information into the contour $L(P_i, P_j)$. An old sensor can communicate with the deployed network if and only if the old sensor is within the bound of a nearby new sensor. If we draw a circle around the old sensor with the radius being the bound, the circled area indicates the coverage of the old sensor. If a point y (new sensor) is located within the circle, then the old sensor can be reused since it can communicate with the new sensor. Furthermore, if y is outside $L(P_0, P_1)$, we have $nd(P_0, y) > nd(P_1, y)$. Therefore if P_0 can be reused, P_1 can also be reused. We summarize the above discussion with the following theorem.

Theorem 3.1 The area that is outside $L(P_i, P_j)$, but inside the circle centered at P_i, is the locus of points C to deploy the sensor network such that both P_i and P_j can be reused. Furthermore, P_i has an equal or larger network distance to C than P_j has. ☐

There are three cases of the intersection of $L(P_i, P_j)$ and the circle centered at P_i. They are

(a) $L(P_i, P_j)$ is totally outside the circle;
(b) $L(P_i, P_j)$ is totally inside the circle;
(c) $L(P_i, P_j)$ intersects with the circle.

If $L(P_i, P_j)$ is totally outside the circle, then P_i cannot be reused in any network that has a larger distance to P_i than to P_j. If $L(P_i, P_j)$ is totally inside the circle, then both P_i and P_j can reused in a network that has a larger network distance to P_i than to P_j. The area that is outside $L(P_i, P_j)$ but inside the circle is the locus to deploy a sensor network in which both old sensors can be reused, subject to the condition that P_i has an equal or larger network distance than P_j. If $L(P_i, P_j)$ intersects the circle, it means that the area that is outside $L(P_i, P_j)$ but inside the circle is the locus to deploy a sensor network in which both old sensors can be reused, subject to the condition that P_i has an equal or larger network distance than P_j.

Suppose we have computed all the $L(P_0, P_j)$ for all $j \neq 0$, and drawn them around P_0 as shown in Fig. 7. Next, we add a circle around P_i with the radius being the bound. Now, if we walk from a point x on the circle straight towards the center P_0, the number of lines we encounter is one less than the number sensors that can be reused if the new network is deployed at x. If the encountered line is part of $L(P_0, P_j)$, P_j can be reused. Note P_0 can always be reused. By walking from all points on the circle, we can find the maximum

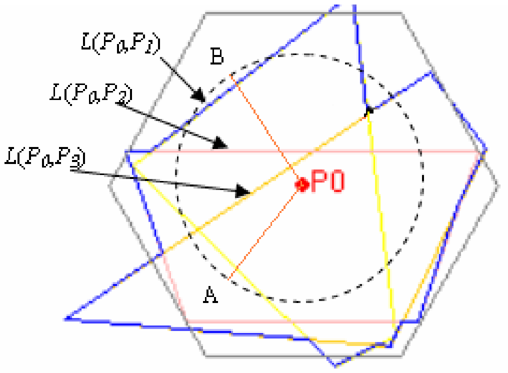


Fig. 7. Combining bounded network bisectors.

number of sensors that can be reused. Of course, all statements here are subject to the condition that P_0 has the largest network distance. We summarize our findings in the following theorem.

Theorem 3.2 Suppose that the maximum number of contours that intersects radii of the bounding circle centered at P_0 is k. The maximum number of sensors that can be reused is $k + 1$ under the condition that P_0 has the largest network distance to the network deployment.

Proof: Subject to the condition that P_0 has the largest network distance, we know that the network starting point C must be located outside the contour $L(P_0, P_j)$. If the starting point is inside the bounding circle centered at P_0, P_0 can be reused. Otherwise, P_0 cannot be reused. For a sensor P_j other than P_0, if the starting point is outside the contour $L(P_0, P_j)$, P_j can be reused as long as P_0 can be reused because, in this case, $nd(P_0, C)$ is greater than $nd(P_j, C)$. Therefore, if we connect a point on the circle to the center P_0, then the number of intersecting contours corresponds to the number of sensors that can be reused, subject to the condition that P_0 is farther from the network than other sensors. It is easy to see that if the maximum number of contours that can intersect a radius is k, then the maximum number of sensors that can be reused for the given bound subject to the condition that P_0 has the largest network distance to the deployment, is $k + 1$. ❑

For example, in Fig. 7, if we walk from point A towards the center P_0, only $L(P_0, P_1)$ is encountered. Therefore, if the network is deployed at A, only old sensors P_0 and P_1 can be reused. However, if we walk from point B towards the center, then $L(P_0, P_1)$, $L(P_0, P_2)$ and $L(P_0, P_3)$ will be encountered. Therefore, in this case, the sensors, P_0, P_1, P_2 and P_3 can be reused when the network is deployed at B.

However, it is impossible for us to inspect every radius to find the maximum number of sensors that can be reused. To solve the maximum sensor reuse problem, we use circular arcs to model the bounded network bisector. As shown in Fig. 8, we add radii at the intersections of the circle and $L(P_0, P_j)$. Each intersection chord corresponds to a circular arc [3]. Each $L(P_0, P_j)$ introduces at most four circular arcs. $L(P_0, P_1)$, $L(P_0, P_2)$, …, $L(P_0, P_{n-1})$ introduce at most a total of $4(n - 1)$ circular arcs.

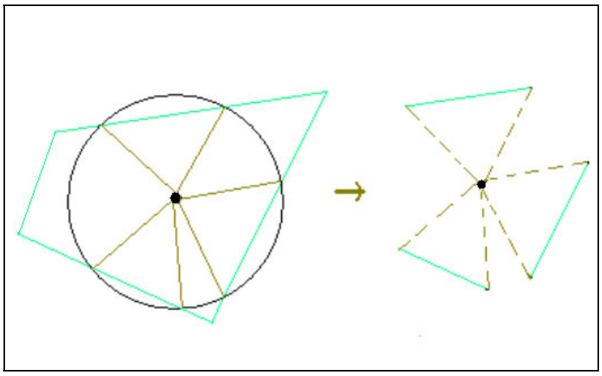


Fig. 8. Circular arcs introduced by intersection chords.

To find the maximum number of circular arcs that intersect a radius, we can first sort all the arc end points. Then we use a sweep line to get the maximum number of the arcs that intersect the sweep line. The maximum number of overlapping arcs for n circular arcs can be found in $O(n \log n)$ time [3].

For each old sensor P_i, we can compute the maximum number of old sensors that can be reused under the condition that P_i has the largest network distance. Next we will try to solve the maximum sensor reuse problem without any conditions. Assume that $T(C)$ is the deployed network in which the maximum number of sensors can be reused, and P_k is the old sensor that has the largest network distance to C. Then the maximum number of old sensors that can be reused is the same as the maximum number of old sensors that can be reused under the condition that P_k is farthest from the network. The following theorem summarizes our findings.

Theorem 3.3 Let k_i ($i = 0, 1, \ldots, n-1$) be the maximum number of old sensors that can be reused under the condition that P_i has a larger network distance than all other old sensors, and let k_m be the maximum among all k_i ($i = 0, 1, \ldots, n-1$). Then k_m is the maximum number of sensors that can be reused.

Proof: Assume that the maximum number of old sensors that can be reused is achieved when the new network T is deployed at C. Further assume P_k has the greatest network distance to $T(C)$ among all the reused old sensors. Therefore, the maximum number of sensors that can be reused must occur when we compute the maximum number of sensors to be reused under the condition that P_k has a greatest network distance. Therefore, the maximum number of sensors that can be reused can be found by finding the largest among all k_i ($i = 0, 1, \ldots, n-1$). ❑

4. THE ALGORITHM AND ITS TIME COMPLEXITY

In this section we present the algorithm to solve the maximum sensor reuse problem for n arbitrarily distributed old sensors, and analyze its time complexity.

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Algorithm: Maximum Sensor Reuse
Input: a set of arbitrarily distributed old sensors $S = \{P_0, P_1, \ldots, P_{n-1}\}$ and a communication
        bound $d$; the cell size and orientation of the new sensor network.
Output: the maximum number of old sensors that can be reused.
BEGIN
  FOR each old sensor $P_i \in S$
    FOR each old sensor $P_j \in S$ ($j \neq i$)
      Make the spreading network of $P_j$, $T(P_j)$;
      Compute network bisector $L(P_i, P_j)$ based on $H(P_i)$ and $T(P_j)$;
      Compute the circular arcs by intersecting $L(P_i, P_j)$ with the circle of radius $d$ and
      centered at $P_i$;
    END FOR;
    Use a sweep line algorithm to find the maximum number, $k_i$, of arcs that can inter-
    sect one radius;
  END FOR;
  Compute $k_m = \max\{k_i \mid i = 0, 1, \ldots, n-1\}$;
  Return $k_m + 1$ as the maximum number of sensors that can be reused.
END.
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Next we show that the time complexity of the algorithm is $O(n^2 \log n)$ if n old sensors are to be considered. Given two points P_i and P_j ($j \neq i$), polygon $L(P_i, P_j)$ is either a triangle or quadrilateral which can be computed in constant time. For each P_i, we have a circular arc graph of a maximum of $4(n-1)$ arcs. The maximum number of arcs that can intersect a radius can be found in $O(n \log n)$ [3]. There are n circular graphs, each of which corresponds to an old sensor. Therefore it takes $O(n^2 \log n)$ time to compute the maximum number of old sensors that can be reused. We summarize our result in Theorem 4.1.

Theorem 4.1 Given a set of n arbitrarily distributed old sensors with a communication bound, and a movable blanket coverage sensor network with a fixed sensor radius and network orientation, the maximum sensor reuse problem can be solved in $O(n^2 \log n)$. ❑

5. SUMMARY

A wireless sensor network is composed of a distributed collection of nodes operating on battery power. When the battery of a sensor node is below a level at which it cannot communicate with others, the network is dead, and it will be replaced by a new sensor network. It is a good idea to deploy the new sensor network so that new sensors are within the limited communication range of the old sensors. In this way the information stored in the old sensors can be retrieved by the new sensors.

This paper proposes two new concepts, network distance and network bisector, and uses them to solve the maximum sensor reuse problem efficiently. The paper shows that the maximum sensor reuse problem can be solved in $O(n^2 \log n)$ time if n old sensors are to be considered.

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Guangbin Fan received his B.S. degree in Computer Science from Shandong University in 1997, M.E. degree in Computer Applications from Renmin University of China in 2000, and Ph.D. degree in Computer Science from the University of Alabama in 2003. Currently, he is an assistant professor with the Department of Computer and Information Science at the University of Mississippi. His research interests include wireless networks and mobile computing, data management, and computational geometry. He is a member of the IEEE and of the ACM.

Jingyuan Zhang received the B.S. degree from Shandong University in 1984, the M.S. degree from Zhejiang University in 1987, and the doctoral degree from Old Dominion University in 1992, all in computer science. He is currently an assistant professor with the Department of Computer Science at the University of Alabama. Prior to joining the University of Alabama, he was an instructor with Ningbo University, an assistant professor with Elizabeth City State University, and a principal computer scientist with ECI Systems and Engineering. Dr. Zhang's current research interests include wireless networks and mobile computing, spatial databases, visualization, and parallel processing. He is a member of the IEEE.