Distributed Protocols for Ensuring Both Coverage and Connectivity of a Wireless Sensor Network

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Wireless sensor networks have attracted a lot of attention recently. Such environments may consist of many inexpensive nodes, each capable of collecting, storing, and processing environmental information, and communicating with neighboring nodes through wireless links. For a sensor network to operate successfully, sensors must maintain both sensing coverage and network connectivity. This issue has been studied in Wang et al. [2003] and Zhang and Hou [2004a], both of which reach a similar conclusion that coverage can imply connectivity as long as sensors' communication ranges are no less than twice their sensing ranges. In this article, without relying on this strong assumption, we investigate the issue from a different angle and develop several necessary and sufficient conditions for ensuring coverage and connectivity of a sensor network. Hence, the results significantly generalize the results in Wang et al. [2003] and Zhang and Hou [2004a]. This work is also a significant extension of our earlier work [Huang and Tseng 2003; Huang et al. 2004], which addresses how to determine the level of coverage of a given sensor network but does not consider the network connectivity issue. Our work is the first work allowing an arbitrary relationship between sensing ranges and communication distances of sensor nodes. We develop decentralized solutions for determining, or even adjusting, the levels of coverage and connectivity of a given network. Adjusting levels of coverage and connectivity is necessary when sensors are overly deployed, and we approach this problem by putting sensors to sleep mode and tuning their transmission powers. This results in prolonged network lifetime.

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1. INTRODUCTION

The rapid progress of wireless communication and embedded microsensing MEMS technologies has made wireless sensor networks possible. Such environments may have many inexpensive wireless nodes, each capable of collecting, storing, and processing environmental information, and communicating with neighboring nodes. In the past, sensors were connected by wirelines. Today, this environment is combined with the novel ad hoc networking technology to facilitate intersensor communication [Pottie and Kaiser 2000; Sohrabi et al. 2000]. The flexibility of installing and configuring a sensor network is thus greatly improved. Recently, a lot of research activities have been dedicated to sensor networks, including the design of physical and medium-access layers [Shih et al. 2001; Woo and Culler 2001; Ye et al. 2002] and routing and transport protocols [Braginsky and Estrin 2002; Ganesan et al. 2001; Heinzelman et al. 2000]. Localization and positioning applications of wireless sensor networks are discussed in Bahl and Padmanabhan [2000], Savvides et al. [2001], and Tseng et al. [2003].

Since sensors may be spread in an arbitrary manner, a fundamental issue in a wireless sensor network is to ensure *coverage* and *connectivity*. Given a sensor network, the coverage issue is concerned with how well the sensing field is monitored by sensors. In the literature, this problem has been formulated in various ways. Coverage can be regarded as a metric to evaluate the quality of service (surveillance) provided by the network. Between a given pair of points in the sensing field, some works focus on finding a path connecting these two points which is best or worst monitored by sensors when an object traverses along the path [Li et al. 2003; Meguerdichian et al. 2001; Meguerdichian et al. 2001; Veltri et al. 2003]. In Huang and Tseng [2003] and Huang et al. [2004], the coverage problem is formulated as one of determining if a 2D/3D-sensing field area is sufficiently *k-covered*, that is, each point in the field is within the sensing ranges of at least k sensors. The proposed approach looks at how the perimeter of each sensor's sensing range is covered, thus leading to efficient polynomial-time algorithms. On the other hand, some works are targeted at particular applications (such as energy conservation [Abrams et al. 2004; Tian and Georganas 2003; Yan et al. 2003]), but the central idea is still related to the coverage issue.

The connectivity issue is concerned with the diversity of communication paths between sensors. This would affect network robustness and communication performance. The *GAF* protocol [Xu et al. 2001] aims to extend the network lifetime by turning off redundant nodes, while keeping the same level of *routing fidelity*, which is defined as uninterrupted connectivity between communicating nodes. GAF imposes a virtual grid on the network and nodes in the same grid coordinate with each other to determine who can sleep and for how long. Chen et al. [2002] presents a connectivity-maintaining protocol, *SPAN*, which can turn off unnecessary nodes such that all active nodes are connected through a communication backbone, and all inactive nodes are directly connected to at least one active node. Maintaining a connected network is also a basic requirement of works targeted at *topology control*, which involves adjusting sensors' transmission power for energy efficiency and collision avoidance [Burkhart et al. 2004; Li and Hou 2004; Wattenhofer et al. 2001].

In this work, we study the relationship between sensing coverage and communication connectivity of a sensor network. Wang et al. [2003] proposes a coverage determination algorithm by looking at how intersection points between sensors' sensing ranges are covered by their neighbors and claims that coverage can imply connectivity as long as sensors' communication ranges are no less than twice their sensing ranges. A *Coverage Configuration Protocol (CCP)* that can provide different degrees of coverage and still maintain communication connectivity is presented. If the communication ranges are less than twice the sensing ranges, Wang et al. [2003] proposes integrating CCP with SPAN [Chen et al. 2002] to provide both sensing coverage and communication connectivity. A similar result is also drawn in Zhang and Hou [2004a], and thus only the coverage problem is addressed. A decentralized density-control algorithm called *Optimal Geographical Density Control (OGDC)* is then proposed to reduce the number of working nodes that cover the network.

It is clear that the results in Wang et al. [2003] and Zhang and Hou [2004a] are not applicable when some sensors' communication ranges are less than twice their sensing ranges even though others are not. Also, both Wang et al. [2003] and Zhang and Hou [2004a] assume that all sensors have the same sensing ranges. In this article, we relax these constraints and show necessary and/or sufficient conditions for a sensor network to be k-covered and k-connected, and to be k-covered and 1-connected. Hence, the results in Wang et al. [2003] and Zhang and Hou [2004a] can be regarded as special cases of what is proposed in this article. Based on these conditions, we then develop decentralized solutions for determining, or even adjusting, the levels of coverage and connectivity of a given network. This results in a prolonged network lifetime. As far as we know, no result has addressed the combined issues of coverage, connectivity, power management, and power control under a single framework as is done in this work. The ability to adjust the levels of coverage and connectivity makes management of the network more flexible. In emergency applications, keeping the network 1-covered and 1-connected may be sufficient. However, when an emergency occurs, higher coverage and connectivity may be needed in an on-the-fly manner. For autoconfiguration purposes, given an arbitrarily deployed sensor network, we can first calculate the coverage and connectivity levels of the network. If the coverage or connectivity level exceeds our expectation, we can make adjustments using the proposed coverage and connectivity selection protocols to prolong the network lifetime without reducing the sensing and communicating capabilities of the network. This work is a significant extension of our earlier work [Huang and Tseng 2003; Huang et al. 2004], which addresses how to determine the level of coverage of a given sensor network but does not consider the network connectivity issue. Our work is the first work allowing an arbitrary relationship between sensing ranges and communication distances of sensor nodes. Information about the difference of sensors' sensing ranges is discussed in Zhang and Hou [2004b].

Some works also consider the coverage and connectivity issue but have different assumptions or applications. Shakkottai et al. [2003] considers a grid-based network consisting of sensors which may fail probabilistically and investigates the coverage, connectivity, and diameter of the network. Inanc et al. [2003] studies the problem of minimizing energy consumption by suspending sensors' sensing and communication activities according to a Markovian stochastic process, ensuring communication connectivity and sensing coverage. However, the definitions of event coverage and path connectivity distinguish our goals from other works. Given a spatial query requesting data of interest in a geographical region, the goal of Gupta et al. [2003] is to select the smallest subset of sensors which are connected and are sufficient to cover the region. The proposed solution is a greedy algorithm which recurrently selects a path of sensors that is connected to an already selected sensor until the given query region is completely covered.

This article is organized as follows. Section 2 gives some preliminaries. Several conditions for coverage and connectivity are presented in Section 3. Decentralized coverage and connectivity determination and adjustment protocols are developed in Section 4. Section 5 presents our simulation results. Section 6 draws our conclusions and future work.

2. PRELIMINARIES AND PROBLEM STATEMENT

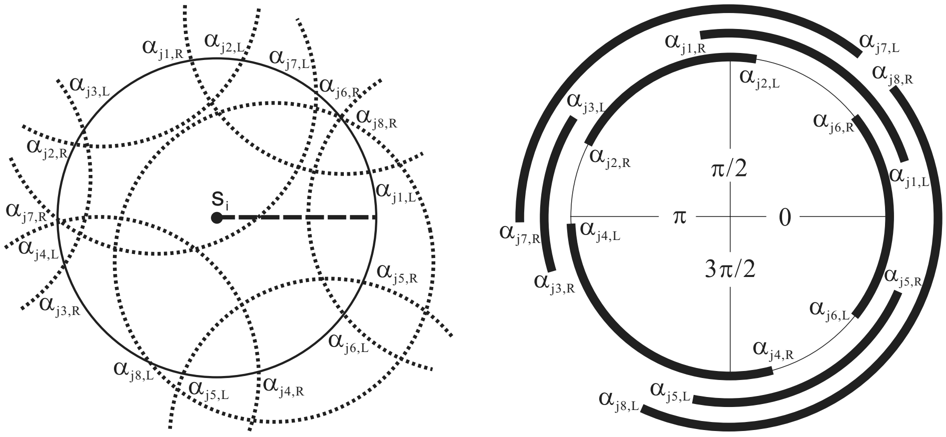
We are given a set of sensors, $S = \{s_1, s_2, \ldots, s_n\}$, in a two-dimensional area A. Each sensor s_i, $i = 1 \ldots n$, is located at a known coordinate (x_i, y_i) inside A and has a sensing distance of r_i and a communication distance of c_i. So, s_i can detect an object/event located within a distance of r_i from itself and talk to another sensor within a distance of c_i. Note that we make no assumption about the relationship of r_i and c_i. Only bidirectional links are considered. So when two sensors can hear each other, we say that there is a communication link, or simply a link, between them.

Definition 1. A point in A is said to be *covered* by s_i if it is within s_i's sensing range. Given an integer k, a point in A is said to be *k-covered* if it is covered by at least k distinct sensors. The sensor network is said to be *k-covered* if every point in A is k-covered.

Definition 2. The sensor network is said to be *1-connected* if there is at least one path between any two sensors. The sensor network is said to be *k-connected* if there are at least k disjointed paths between any two sensors.

The deployment of sensors is not of concerned in our work, and we assume the network is at least 1-covered. We formulate the general form of the coverage and connectivity problem as follows.

Definition 3. Given any two integers k_s and k_c, the *k_s-covered and k_c-connected problem*, or the (k_s, k_c)-*CC* problem, is a decision problem whose goal is to determine whether the sensor network is k_s-covered and k_c-connected.



(a) (b)

Fig. 1. Determining the perimeter coverage of a sensor s_i.

As far as we know, the general (k_s, k_c)-*CC* problem has not been well addressed yet. In Huang and Tseng [2003], the coverage problem has been solved in an efficient way. Following, we briefly review the result which will be used as a basis for our derivation. Given any sensor, Huang and Tseng [2003] try to look at the perimeter that bounds the sensor's sensing range (for convenience, this may be simply referred to as the perimeter of the sensor). The algorithm essentially determines the coverage level of the sensing field A by determining the perimeter of each sensor.

Definition 4. Consider any two sensors s_i and s_j. A point p on the perimeter of s_i is *perimeter-covered by* s_j if this point is within the sensing range of s_j, that is, the distance between p and s_j is less than r_j. A point p on the perimeter of s_i is k*-perimeter-covered* if it is perimeter-covered by at least k sensors other than s_i itself. Sensor s_i is k*-perimeter-covered* if all points on the perimeter of s_i are perimeter-covered by at least k sensors other than s_i itself.

THEOREM 1 [HUANG AND TSENG 2003]. *The whole network area* A *is* k*-covered if and only if each sensor in the network is* k*-perimeter-covered.*

The approach in Theorem 1 looks at how the perimeter of each sensor's sensing range is covered by its neighbors. For each sensor s_i, it tries to identify all neighboring sensors which can contribute some coverage to s_i's perimeter. Specifically, for each neighboring sensor s_j, we can determine the angle of s_i's arch, denoted by $[\alpha_{j,L}, \alpha_{j,R}]$, which is perimeter-covered by s_j. Placing all angles $[\alpha_{j,L}, \alpha_{j,R}]$ on $[0, 2\pi]$ for all j's, it is easy to determine the level of perimeter coverage of s_i. For example, Figure 1(a) shows how s_i is covered by its neighbors (shown in dashed circles). Mapping these covered angles in Figure 1(b), it is easy to decide that s_i is 1-perimeter-covered. It is shown in Huang and Tseng [2003] that Theorem 1 can be converted into an efficient coverage determination algorithm. It is to be noted that it makes no sense to consider the perimeter of a sensor exceeding the sensing field A. So we only consider the perimeters of sensors inside A. In the extreme case that a sensor's sensing range contains A, we simply ignore it and consider that it contributes a coverage of 1 to A.

3. CONDITIONS FOR NETWORK COVERAGE AND CONNECTIVITY

In this section, we propose theoretical foundations and necessary and/or sufficient conditions to solve the (k_s, k_c)-CC problem. We make no assumption on the relationship between r_i and c_i of sensor s_i. We show conditions for a sensor network to be k-covered and k-connected, and to be k-covered and 1-connected. We also show under what conditions a sensor network may provide sufficient coverage by multiple connected components.

3.1 Theoretical Fundamentals

The definition of perimeter coverage proved useful to determine the coverage level of a sensor network in Huang and Tseng [2003]. However, the network connectivity issue has not been studied. For a sensor network to operate successfully, sensors must maintain both sensing coverage and network connectivity. Below we develop some fundamentals to achieve this goal.

Definition 5. Consider any sensor s_i. The *neighboring set* of s_i, denoted as $N(i)$, is the set of sensors each of whose sensing region intersects with s_i's sensing region.

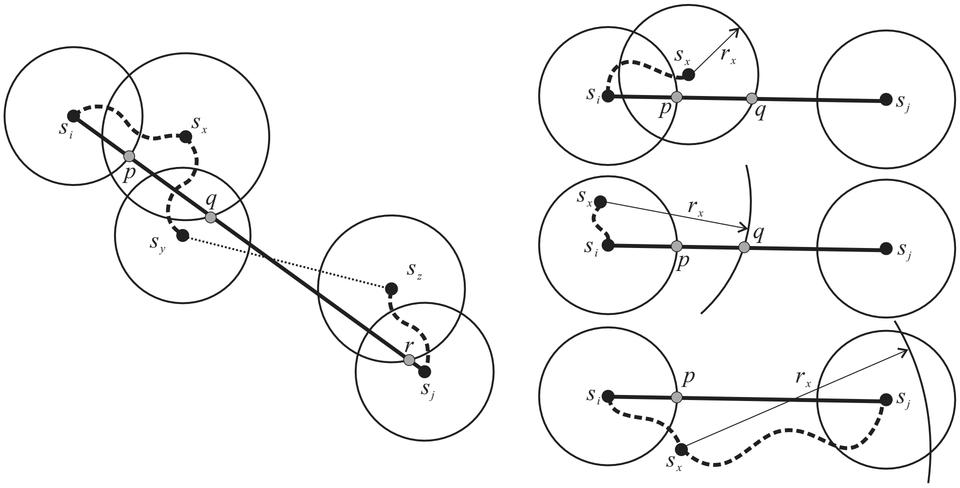
Note that neighbors are concerned with how sensors' coverage areas overlap, and should not be confused with communication links, which are concerned with sensors' transmission distances.

Definition 6. Consider any sensor s_i. We say that s_i is *k-direct-neighbor-perimeter-covered*, or *k-DPC*, if s_i is k-perimeter-covered and s_i has a link to each node in $N(i)$. Similarly, we say that s_i is *k-multihop-neighbor-perimeter-covered*, or *k-MPC*, if s_i is k-perimeter-covered and s_i has a (single- or multi-hop) path to each node in $N(i)$.

These definitions allow us to derive some coverage and connectivity properties of a network.

LEMMA 1. *Consider any two sensors s_i and s_j. If each sensor in S is 1-MPC, there must exist a communication path between s_i and s_j.*

PROOF. This proof is by construction. If s_i's sensing region intersects with s_j, by Definition 6, there must exist a path between s_i and s_j, which proves this lemma. Otherwise, draw a line segment L connecting s_i and s_j, as illustrated in Figure 2(a). Let L intersect s_i's perimeter at point p. Since s_i is 1-MPC, by Definition 6, there must exist a sensor s_x in $N(i)$ which covers p and has a path to s_i. In addition, either s_x must cover s_j, or s_x's perimeter must intersect L at a point, namely q, which is closer to s_j than p is. Figure 2(b) shows several possible combinations of s_x and r_x. In the former case, by Definition 6, there must exist a path between s_x and s_j, and thus s_i and s_j, which proves this lemma. In the latter case, there must exist another sensor s_y in $N(x)$ which covers q. We can repeat



(a) (b)

Fig. 2. Proof of Lemma 1: (a) the path construction, and (b) possible cases of s_x.

the argument until a sensor s_z is found which either covers s_j or intersects L at a point, say r, inside s_j's sensing range. Note that since the number of sensors is finite, the construction must eventually terminate and the path from s_i must reach s_j. Otherwise, the intersection point of s_j's perimeter and L is not covered by any sensor. As a result, there must exist a path between s_z and s_j which proves this lemma. □

THEOREM 2. *A sensor network is k-covered and 1-connected if and only if each sensor is k-MPC.*

PROOF. For the if part, we have to guarantee both the coverage and connectivity. The fact that the network is k-covered has been proved by Theorem 1 because each sensor which is k-MPC is also k-perimeter-covered. In addition, Lemma 1 can guarantee that the network is 1-connected, hence proving the if part.

For the only if part, we have to show that each sensor is k-perimeter-covered and has a path to each sensor whose sensing region intersects with its region. The first concern can be ensured by Theorem 1, while the second concern can be ensured by the fact that the network is 1-connected. □

THEOREM 3. *A sensor network is k-covered and k-connected if each sensor is k-DPC.*

PROOF. Coverage has been guaranteed by Theorem 1 since a sensor which is k-DPC is k-perimeter-covered by definition. For the connectivity part, if we remove any $k - 1$ nodes from the network, it is not hard to see that each of the rest of sensors must remain 1-DPC. This implies that these sensors are also 1-MPC, and, by Lemma 1, there must exist a path between any pair of these sensors. As a result, the network is still connected after the removal of any $k-1$ nodes, which proves this theorem. □

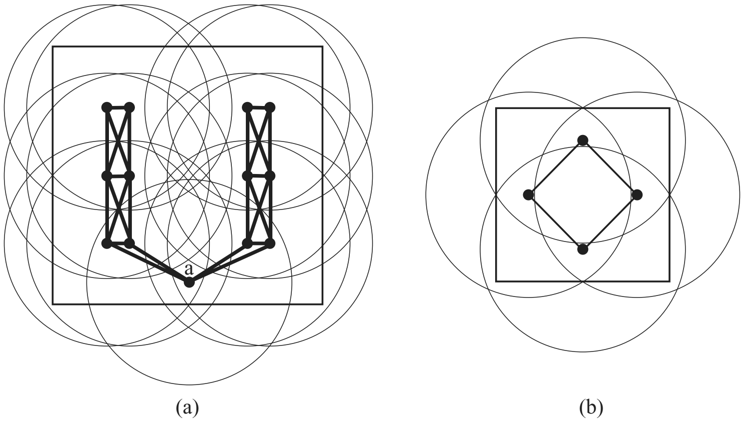


Fig. 3. Observations of Theorem 2 and Theorem 3: (a) the network is 2-covered and 1-connected. The removal of sensor a will disconnect the network, and (b) the network is 2-covered and 2-connected but no sensor is 2-DPC. Note that the sensing and communication ranges of each sensor are the same and are represented by circles.

Following we make some observations about Theorem 2 and Theorem 3. First, a major difference is that Theorem 2 can guarantee only 1 connectivity, while Theorem 3 can guarantee k connectivity. This is because, in a network where each sensor is k-MPC, the removal of any sensor may disconnect the network. For example, in the network in Figure 3(a), each sensor is 2-MPC. By Theorem 2, the network is 2-covered and 1-connected. However, if we remove sensor a, the network will be partitioned into two components. Interestingly, although the network remains 2-covered, it is no longer connected.

Second, the reverse direction of Theorem 3 may not be true. That is, if a network is k-covered and k-connected, sensors in this network may not be k-DPC. Figure 3(b) shows an example in which the network is 2-covered and 2-connected. However, each node has a neighbor (with overlapping sensing range) to which there is no direct communication link.

Third, Theorem 3 is stronger than the results in Wang et al. [2003] and Zhang and Hou [2004a]. It is clear that when two sensors have overlapping sensing range, there is a direct communication link between these two sensors if the communication distance is at least twice the sensing distance. So what can be determined by Wang et al. [2003] and Zhang and Hou [2004a] can also be determined by Theorem 3. Furthermore, when the previous assumption does not exist, Theorem 3 may still work while Wang et al. [2003] and Zhang and Hou [2004a] do not. For example, Theorem 3 can determine that the network in Figure 4 is 1-covered and 1-connected when some sensors' communication ranges are less than twice their sensing ranges.

3.2 Looser Connectivity Conditions

Definition 7. The *direct neighboring set* of s_i, denoted as $DN(i)$, is the set of sensors each of which has a communication link to s_i and whose sensing region intersects with s_i's sensing region. Similarly, the *multihop neighboring set* of s_i,

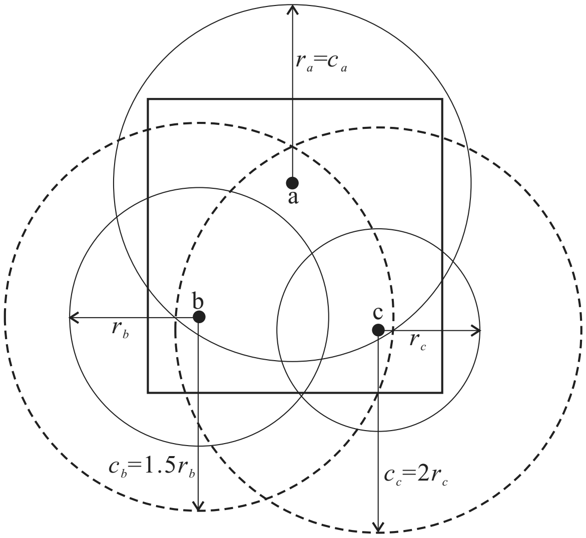


Fig. 4. An example comparing Theorem 3 with results in the literature. Solid circles and dotted circles are sensors' sensing ranges and communications ranges, respectively.

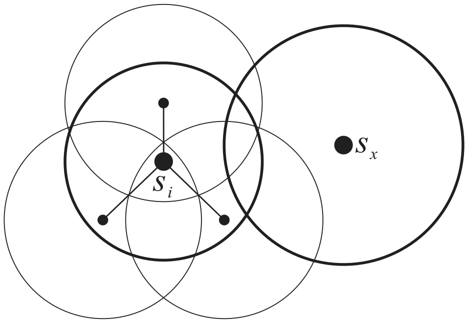


Fig. 5. An example that k-LDPC is looser than k-DPC.

denoted as $MN(i)$, is the set of sensors each of which has a (single or multihop) path to s_i and whose sensing region intersects with s_i's.

Definition 8. Consider any sensor s_i. We say that s_i is *k-loose-direct-neighbor-perimeter-covered*, or *k-LDPC*, if s_i is k-perimeter-covered by and only by nodes in $DN(i)$. Similarly, we say that s_i is *k-loose-multihop-neighbor-perimeter-covered*, or *k-LMPC*, if s_i is k-perimeter-covered by and only by nodes in $MN(i)$.

We comment that, for any sensor s_i, $DN(i) \subseteq MN(i) \subseteq N(i)$. So the definition that s_i is k-LDPC is looser than that of s_i is k-DPC in the sense that k-DPC guarantees that there is a link from s_i to each of $N(i)$, but k-LDPC only guarantees that there is a link from s_i to each of $DN(i)$. For example, consider sensor s_i in Figure 5. There is another sensor s_x whose sensing range intersects with

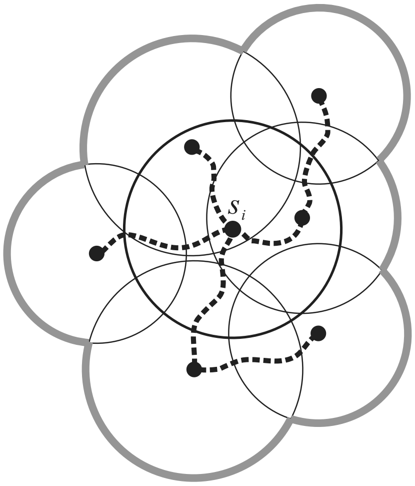


Fig. 6. Proof of the Lemma 2.

sensor s_i's sensing range but who has no link to s_i, that is, $s_x \in N(i) - DN(i)$. Without taking s_x into account, s_i is 1-perimeter-covered by and only by nodes in $DN(i)$ and is thus 1-LDPC. However, s_i is not 1-DPC since it does not have a link to each node in $N(i)$. The definition of k-LMPC is looser than that of k-MPC in a similar sense.

LEMMA 2. *If each sensor in S is 1-LMPC, then the network can be decomposed into a number of connected components each of which 1-covers the sensing field A.*

PROOF. This proof is by construction. For any sensor s_i, we try to construct a connected component which fully covers A. (However, the proof does not guarantee that s_i has a path to every sensor.) If s_i's sensing region can fully cover A, the construction is completed. Otherwise, by Definition 8, nodes in $MN(i)$ must perimeter-cover s_i's perimeter and each has a path to s_i, as illustrated in Figure 6. In addition, nodes in $MN(i)$, together with s_i, form a larger coverage region which is bounded by perimeters of nodes in $MN(i)$. If A is already fully covered by this region, the construction is completed. Otherwise, since each sensor is 1-LMPC, we can repeat similar arguments by extending the coverage region, until the whole field A is covered. □

THEOREM 4. *A sensor network can be decomposed into a number of connected components each of which k-covers A if and only if each sensor is k-LMPC.*

THEOREM 5. *A sensor network can be decomposed into a number of k-connected components each of which k-covers A if each sensor is k-LDPC.*

The proof of Theorem 4 (respectively, Theorem 5) is similar to Theorem 2 (respectively, Theorem 3) by replacing Lemma 1 with Lemma 2. We comment that, although the results of Theorem 4 and Theorem 5 do not seem to be very

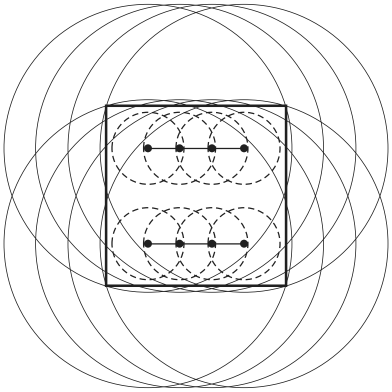


Fig. 7. An example of two connected components each of which 1-covers A.

desirable if one only knows that there are multiple 1- or k-connected components in the network, this is what we have to face in practice when deploying a sensor network. An example of Theorem 4 is shown in Figure 7. Due to the relatively small communication ranges compared to sensing ranges, the network is partitioned into two connected components. However, each component still provides sufficient 1-coverage.

To summarize, Theorem 4 and Theorem 5 only guarantee that the network can be sufficiently covered by each connected component, while Theorem 2 and Theorem 3 can guarantee both coverage and connectivity of the whole network. When $DN(i) = N(i)$ or $MN(i) = N(i)$ for each sensor s_i, these theorems converge. Also observe that Theorem 4 and Theorem 5 are more practical because each sensor only needs to collect its reachable neighbors' information to make its decision. Most applications can be satisfied if a subset of sensors is connected and can provide sufficient coverage. The redundance caused by multiple components may be eliminated by a higher level coordinator, such as the base station, to properly schedule each component's working time so that no two components of the network are active at the same time.

4. DISTRIBUTED COVERAGE AND CONNECTIVITY PROTOCOLS

The quality of a sensor network can be reflected by the levels of coverage and connectivity that it offers. The previous results provide us a foundation to determine, or even select, the quality of a sensor network by looking at how each sensor's perimeter is covered by its neighbors. Section 4.1 shows how to translate there results to fully distributed coverage and connectivity determination protocols. When sensors are overly deployed, the coverage and connectivity of the network may exceed our expectation. In this case, Section 4.2 proposes a distributed quality selection protocol to automatically adjust its coverage and connectivity by putting sensors into sleep mode and tuning sensors' transmission power. In Section 4.3, we show how to integrate the previous results into one energy-saving protocol to prolong the network lifetime.

4.1 Coverage and Connectivity Determination Protocols

The goal of the protocol is to determine the levels of coverage and connectivity of the network. For a sensor to determine how its perimeter is covered, first it has to collect how its one-hop neighboring sensors' sensing regions intersect with its sensing region and calculate the level of its perimeter coverage. Periodical *BEACON* messages can be sent to carry sensors' location and sensing range information. On receiving such *BEACON* messages, a sensor can determine who its direct neighbors are and how its perimeter is covered by them. As reviewed in Section 2, determining a sensor's perimeter coverage can be done efficiently in polynomial time [Huang and Tseng 2003]. If the level of perimeter coverage is determined to be k in this step, we can say that this sensor is k-LDPC.

If the previous level of coverage, k, is below our expectation, the sensor can flood a *QUERY* message to its neighbors to find out who else is having overlapping sensing regions with itself. The flooding can be a localized flooding (with a certain hop limit) to save cost. Each sensor who receives the QUERY message has to check if its sensing region intersects with the source node's sensing region. If so, a *REPLY* message is sent to the source node. In so doing, the source node can calculate its level of perimeter coverage based on the received REPLY messages. If the level of perimeter coverage is determined to be k' in this step ($k' \geq k$), we can say that this sensor is k'-LMPC. If this value is still below our expectation, we can take an incremental approach by flooding another QUERY with a larger hop limit until the desired level of coverage is reached or the whole network is flooded.

After these steps, each sensor can report its exploring result to the base station or a certain centralized sensor. Then the base station can determine the coverage and connectivity levels of the network. There are three possible cases. If each sensor is at least k-LDPC, the network is k-covered and k-connected. If some sensors are at least k-LMPC, while others are at least k-LDPC, the network is k-covered and 1-connected. If there exists some sensors that are neither k-LDPC nor k-LMPC, then the network must be disconnected. In this case, it is possible that the network is still sufficiently covered but is partitioned. For example, if we remove sensor a in Figure 3(a), the network is disconnected into two parts. Although these two parts together provide 2-level coverage, since sensors are unable to exchange information, such a situation can not be determined by the network.

4.2 Coverage and Connectivity Selection Protocols

When sensors are overly deployed, one may want to put some sensors into sleep mode to reduce the level of coverage. One may further reduce the transmission power of sensors to reduce the network connectivity. As far as we know, the combination of these mechanisms has not been studied in the literature. In this section, we explore these two possibilities based on the foundations developed in Section 3.

The basic idea is as follows. Suppose that we are given a sensor network that is k_{init}-covered and k_{init}-connected (this can be decided by Theorem 4 and the protocol in Section 4.1). If such levels of coverage and connectivity are beyond our expectation, we propose a protocol to modify the network to k_s-covered and k_c-connected such that $k_{init} \geq k_s \geq k_c \geq 1$. First, in Section 4.2.1, we present a sleep protocol to reduce the network to k_s-LDPC (which means k_s-covered and k_s-connected) by putting some sensors into sleep mode. Then, in Section 4.2.2, a power control protocol is presented to reduce the network to k_c-LDPC. This results in a k_s-covered, k_c-connected network because reducing the transmission power of a sensor will not affect its sensing range.

4.2.1 *The Sleep Protocol.* In this protocol, each sensor only needs to know the locations and sensing regions of its two-hop neighbors that are in the active state. Two-hop neighbor information can be obtained by attaching the direct neighbor information of each sensor in its periodical BEACON messages. The information should include a sensor's location, sensing range, and current power setting. Since wireless sensor networks are typically considered static, the cost to exchange such information should be low. Suppose that the network is k_{init}-LDPC. The purpose of this protocol is to put some sensors into the sleep mode such that the network is at least k_s-LDPC, where $k_{init} \geq k_s$. For each sensor S_x that intends to go to sleep, it will execute the following procedure.

(1) For each s_y that is a direct neighbor of s_x such that s_x and s_y have overlapping in their sensing regions, let $p(s_x, s_y)$ be the perimeter of s_y's sensing range that is covered by s_x's sensing range. Sensor s_x then calculates the level of coverage of $p(s_x, s_y)$. If the level of coverage is at least k_s+1, then s_x is a candidate.

(2) If s_x is a candidate for each s_y that is a direct neighbor of s_x, then s_x is eligible to go to the sleep mode. Then s_x waits for a random backoff time T_{rand} and overhears if there is any other sleeping request. (One possibility is to set T_{rand} according to s_x's remaining energy.) If any sleeping request is heard, s_x will go back to Step (1), hold for another random period, and try again. Otherwise, s_x will send a *SLEEP* message to each of its neighbors and wait for their responses by setting up a timer T_s.

(3) Each s_y which is a neighbor of s_x can reply a *GRANT-SLEEP* message to s_x if it has no pending grant currently. Otherwise, a *REJECT-SLEEP* message is replied. Note that to avoid erroneously putting too many sensors to sleep and to maintain synchronization, a sensor can have at most one pending grant at a time. Specifically, a *GRANT-SLEEP* message is clear from the pending status once a *CONFIRM*/*WITHDRAW* message is received (see Step (4)).

(4) If s_x can collect a *GRANT-SLEEP* message from each of its neighbors, s_x broadcasts a *CONFIRM* message to its neighbors and then goes to sleep. If any *REJECT-SLEEP* message is received or the timer T_s expires, s_x broadcasts a *WITHDRAW* message to its neighbors.

Note that in the Step (1), s_x needs to know all of the direct neighbors of sensor s_y. Since s_x and s_y are direct neighbors, these sensors are s_x's two-hop neighbors. Figure 8 shows an example of the protocol. If s_x intends to go to sleep, it will check the perimeter $p(s_x, s_y)$ (shown in the thick line) since

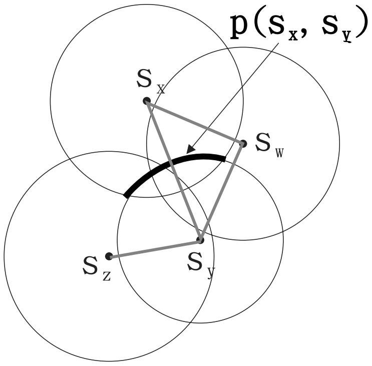


Fig. 8. An example of the Sleep Protocol. Sensor s_x is a candidate with respect to sensor s_y.

$p(s_x, s_y)$ is also covered by s_z and s_w. If the target coverage is $k_s = 1$, then s_x is a candidate with respect to s_y. Also note that the timer T is necessary because we assume an unreliable broadcast.

4.2.2 *The Power Control Protocol.* The aim of the power control protocol is to reduce the transmission power of sensors to save energy. Since this operation does not affect the sensing unit(s), the sensing capability of sensors (and thus the level of coverage of the network) is not reduced. Suppose that the network is k_s-LDPC. The purpose of this protocol is to reduce some sensors' transmission power to make the network at least k_c-LDPC, where $k_s \geq k_c$. This results in a k_s-covered, k_c-connected network.

This protocol assumes that each sensor knows the information of its two-hop neighbors. For sensor s_x which intends to reduce its transmission powers, it executes the following procedure.

(1) Let s_y be the direct neighbor of s_x that is farthest from s_x. Sensor s_x then computes the perimeter coverage of the segments $p(s_x, s_y)$ and $p(s_y, s_x)$. If both segments are at least $(k_c + 1)$-LDPC, s_x is allowed to conduct power control. Then s_x waits for a random backoff time T_{rand} and overhears if there is any other disconnecting request. If any request is heard, s_x will go back to Step (1), hold for another random period, and try again. Otherwise, s_x will send a *DISCONNECT* message to s_y and wait for its response by setting up a timer T_p.

(2) On receipt of s_x's disconnecting request, if s_y has no pending disconnecting request currently, s_y can reply with a *GRANT-DISC* message to s_x. Otherwise, a *REJECT-DISC* is replied. Note that a *DISCONNECT* message is clear from the pending status once a *GRANT-DISC* / *REJECT-DISC* message is received or the timer T_p expires.

(3) If a *GRANT-DISC* message is received, s_x can reduce its transmission power such that only its second-farthest direct neighbor is covered and go back to Step (1) to try to further reduce its transmission power. Otherwise, a *REJECT-DISC* message will stop s_x from reducing its transmission power.

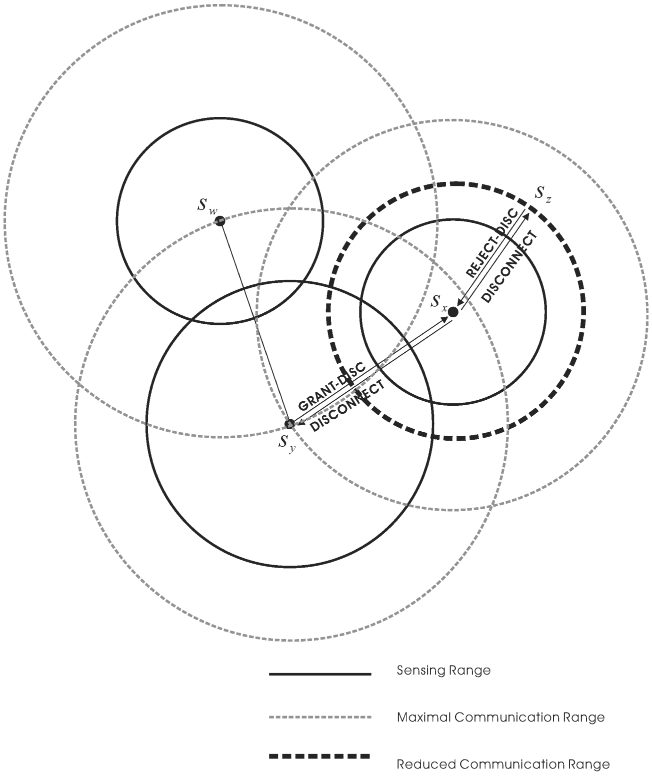


Fig. 9. A power control protocol example.

Note that in the protocol just presented, sensor s_y may not be able to reduce its transmission power even if s_x successfully reduces its power. This is because s_y may need to maintain connectivity with other neighbors that are farther away than s_x. Another comment is that here we choose to let s_x reduce its power step-by-step. The concern is for fairness.

Figure 9 shows an example. Initially, the network is 2-covered and 2-connected (i.e., $k_{init} = 2$). We only consider sensor s_x and its two neighbors s_y and s_z. We will disconnect the communication link between s_x and its farthest-direct neighbor, s_y, by power control. First, s_x examines its intersection with s_y. Both segments $p(s_x, s_y)$ and $p(s_y, s_x)$ are 2-LDPC, so s_x sends a *DISCONNECT* message to s_y, which will agree by replying a *GRANT-DISC* message. Then s_x can reduce its transmission power to the level that can reach the next farthest neighbor s_z. Next, s_x examines its intersection with s_z. Both segments $p(s_x, s_z)$ and $p(s_z, s_x)$ are 2-LDPC, so s_x sends a *DISCONNECT* message to s_z. Suppose that s_z has a pending disconnecting request currently, it will reply a *REJECT-DISC* message to s_x. Then s_x stops its procedure. Note that in this scenario, s_y may not necessarily reduce its transmission power even if it grants s_x's request to reduce power. For example, s_y may not be able to reduce its power because s_w wants to remain connected with s_y. In order to maintain connectivity with s_w, s_y can still reach s_x. This results in an asymmetric link between s_x and s_y

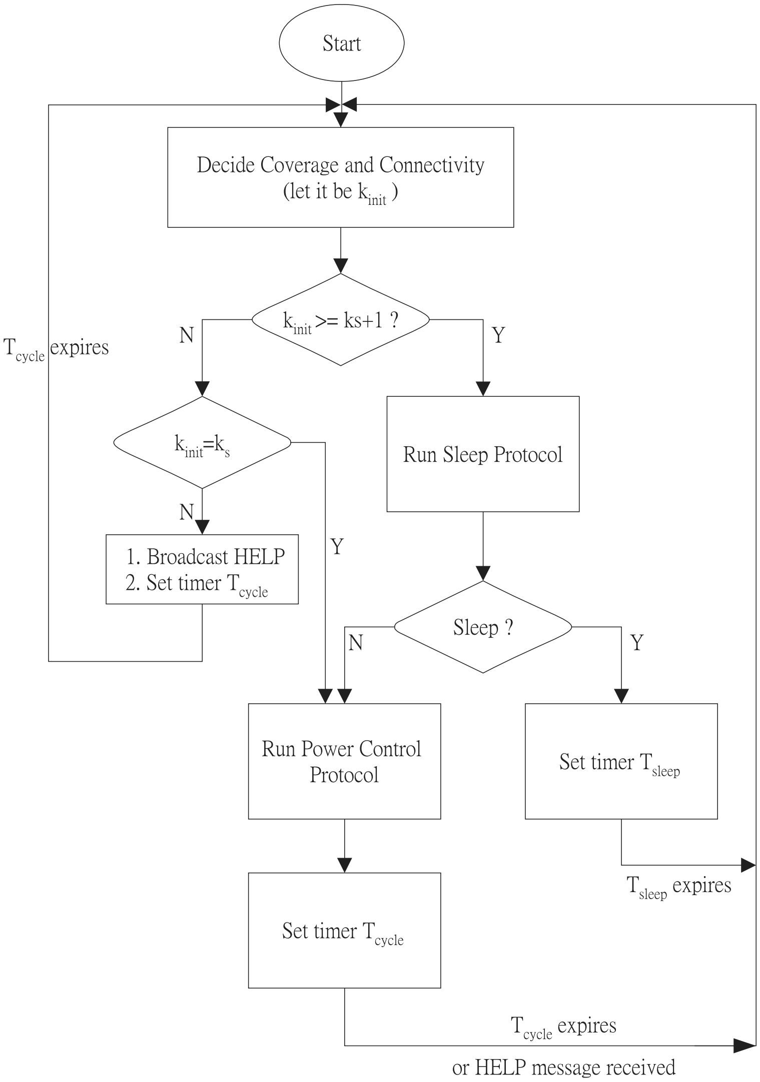


Fig. 10. An integrated energy-saving protocol.

(i.e., the transmission power of s_x cannot reach s_y, but the transmission power of s_y can reach s_x). Therefore, only s_x can benefit from the transmission power.

4.3 An Integrated Energy-Saving Protocol

In Figure 10, we show how to integrate the above coverage and connectivity determination protocol, sleep protocol, and power control protocol together into one protocol. The purpose is to save energy while maintaining the quality of the network. Basically, these subprotocols are executed in this order. We assume that the goal is to achieve a k_s-covered, k_c-connected network, where $k_s \geq k_c$. In particular, we set up two timers, one called T_{sleep} for sleeping sensors to wake themselves up, and one called T_{cycle} for sensors to recheck their local coverage and connectivity (this is to prevent neighboring sensors from running out of batteries, thus resulting in a network weaker than k_s-covered and k_c-connected). Also, a new *HELP* message is designed for sensors to call others' assistance to increase the coverage and connectivity of the network (if possible) when some sensors run out of energy. Note that whenever a sensor goes to the initial state, it will use the largest transmission power to determine its local network coverage and connectivity. For example, this applies to a sensor when it receives a *HELP* message under a reduced transmission power status.

5. SIMULATION RESULTS

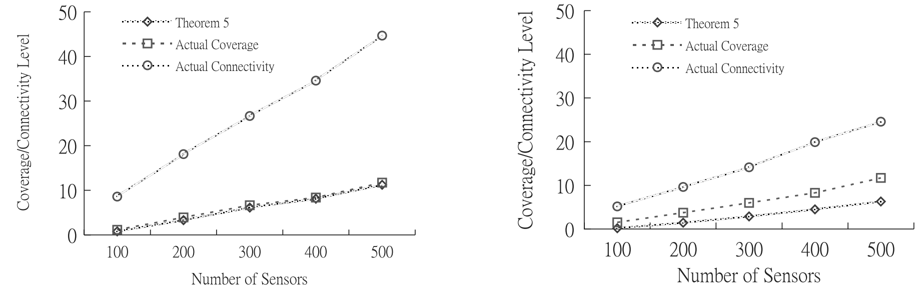
In this section, we present two sets of simulation experiments. Experiment 1 tests the network coverage and connectivity at different sensing ranges and communication ranges. Experiment 2 evaluates the performance of the proposed energy-saving protocol.

5.1 Experiment 1: Coverage and Connectivity

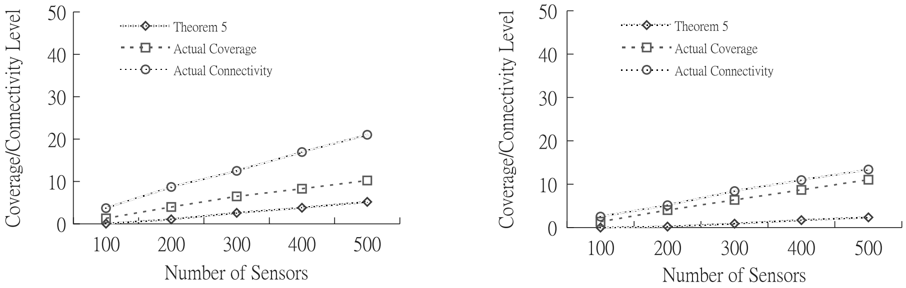
We have developed a simulator to compare the network coverage and connectivity calculated by Theorem 5 and by an exhausted search algorithm. All results in this section are from averages of at least 100 runs. The simulation environment is a 100×100 square area, on which sensors are randomly deployed. The sensing range and communication range of each sensor are uniformly distributed in certain ranges.

Figure 11 shows the coverage and connectivity under different communication ranges. Note that Theorem 5 may not be able to find the exact coverage and connectivity levels because it only relies on local information. Our goal is to compare the results obtained by Theorem 5 (which implies coverage as well as connectivity) against the minimum of the actual coverage and actual connectivity obtained by an exhaustive search. So Figure 11(a) represents an ideal situation because what is found by Theorem 5 matches closely with the actual values. The gaps increase as we move to Figure 11(b), (c), and (d). This is because the ratios of average communication range to average sensing range are reduced, which means that a sensor may not know of the existence of another sensor which overlaps with its own sensing range if it only examines its direct neighbors. So a certain degree of coverage and connectivity is not discovered by Theorem 5.

Next, we keep the sensing ranges fixed, but change the communication ranges variations. Figure 12 shows the coverage and connectivity in a 300-node network when we vary the mean and variation of communication ranges. Note that at each point of Figure 12(a), sensors' communication ranges have no variation, while at each point of Figure 12(b), the variation range is 20. Although in both cases Theorem 5 finds about the same values of coverage and connectivity, since the actual connectivity reduces, Theorem 5 matches more closely the actual situations in the case of Figure 12(b). In Figure 13, we conduct the similar simulation by keeping the communication ranges unchanged but changing the mean and variation of the sensing ranges. The trend is similar—Theorem 5

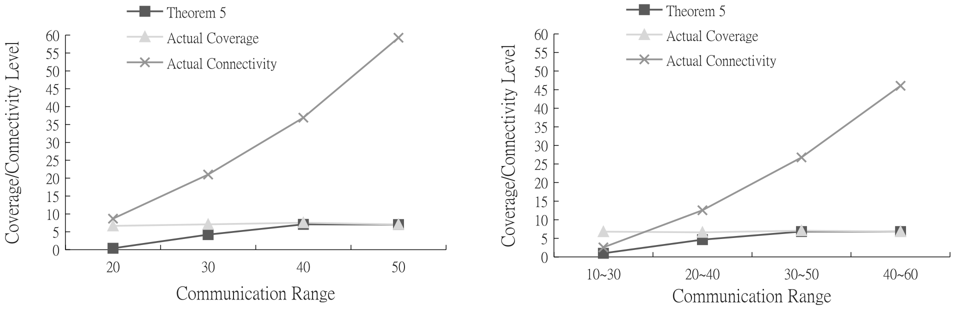


(a) Sensing range = 15~25, Communication range = 30~50 (b) Sensing range = 15~25, Communication range = 20~60



(c) Sensing range = 15~25, Communication range = 20~40 (d) Sensing range = 15~25, Communication range = 15~45

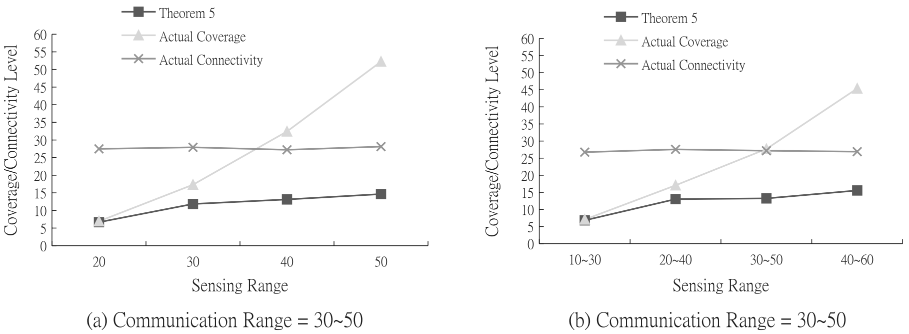
Fig. 11. Network coverage and connectivity under different communication ranges.



(a) Sensing Range = 10~30 (b) Sensing Range = 10~30

Fig. 12. Network coverage and connectivity under different means and variations of communication ranges.

matches the actual situations more closely when there are larger variations in sensing ranges. Also, by comparing Figure 12 and Figure 13, we observe that the gaps reduce when the ratios of the average communication range to the average sensing range increase. The reason is that as the ratio increases, a sensor is able to collect more information about its neighborhood.



(a) Communication Range = 30~50 (b) Communication Range = 30~50

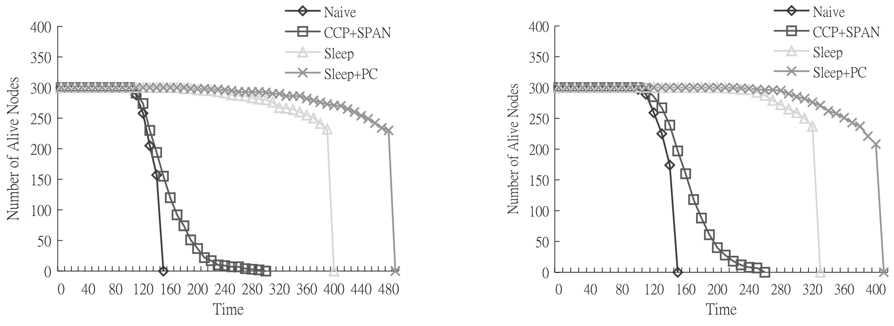
Fig. 13. Network coverage and connectivity under different means and variations of sensing ranges.

5.2 Experiment 2: Network Lifetime

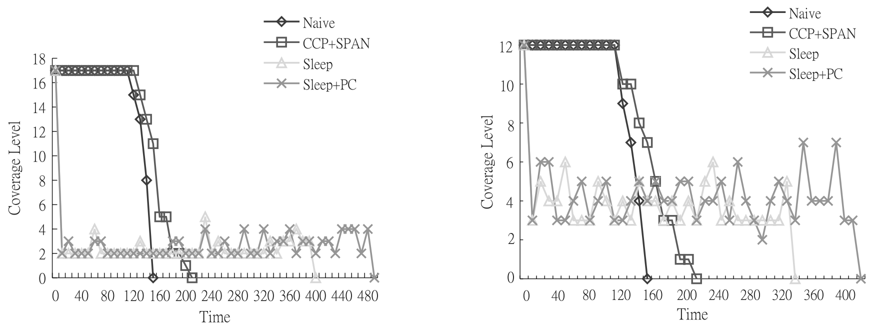
This section verifies our integrated energy-saving protocol for prolonging network lifetime while ensuring both coverage and communication quality. We consider three performance metrics: number of alive nodes, coverage level, and connectivity level. In these experiments, there are 300 sensors randomly deployed in a 100 × 100 square area with sensing range $= 15 \sim 25$ units, communication range $= 30 \sim 50$ units, and initial energy $= 8{,}000 \sim 12{,}000$ units (all in a uniform distribution). Our goal is to achieve a k_s-covered and k_c-connected network. We sample the network status every 10 seconds. We assume a constant traffic rate for each sensor, and the energy cost of each transmission is proportional to a sensor's transmission range. The energy cost for sensing is also proportional to a sensor's sensing range [Lu et al. 2005]. Therefore, for each sensor s_i, the energy consumed every second is proportional to the sum of its sensing range r_i and its current communication range c_i. Although this is a simplified assumption, if the energy cost of each transmission is proportional to a sensor's transmission distance raised to a factor of 2 or 4, our power control scheme should demonstrate even more saving in energy consumption.

Two versions of protocols are evaluated, one with the Sleep protocol only and the other with Sleep+Power Control protocol (denoted by Sleep+PC). We compare our results against a naive protocol where all sensors are always active, and the CCP+SPAN protocol [Wang et al. 2003]. CCP (Coverage Configuration Protocol) is a protocol that can dynamically configure a network to achieve guaranteed degrees of coverage and connectivity if sensors' communication ranges are no less than twice their sensing ranges. If sensors' communication ranges are less than twice their sensing ranges, Wang et al. [2003] suggests integrating CCP with SPAN which is a decentralized protocol that tries to conserve energy by turning off unnecessary nodes while maintaining a communication backbone composed of active nodes.

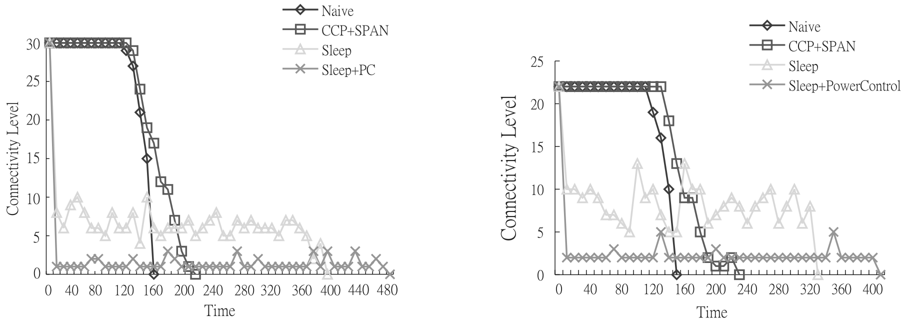
Figure 14(a) shows the number of alive sensors when the goal is to maintain a 2-covered and 1-connected network. In the naive protocol, because nodes are always active, the number of alive sensors drops sharply at around 150s. Sensors in CCP+SPAN protocol fail at a slower speed. Both Sleep and



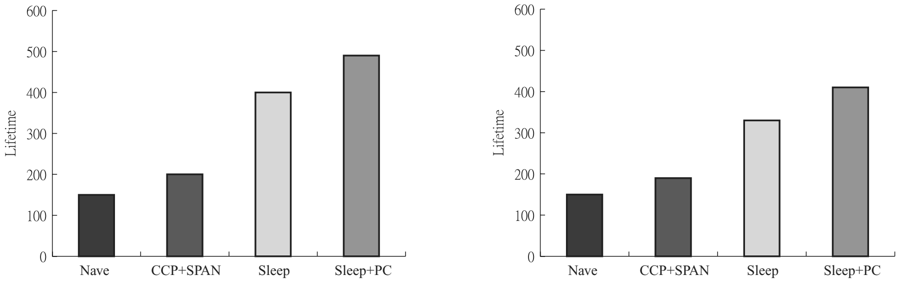
(a) $k_s = 2$, $k_c = 1$ (e) ks = 3, kc = 2



(b) ks = 2, kc = 1 (f) ks = 3, kc = 2

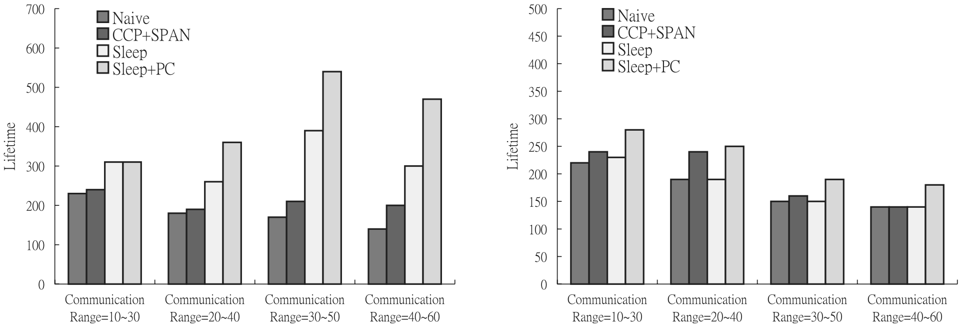


(c) ks = 2, kc = 1 (g) ks = 3, kc = 2



(d) ks = 2, kc = 1 (h) ks = 3, kc = 2

Fig. 14. Comparisons of the naive, CCP+SPAN, Sleep, and Sleep+PC protocols.

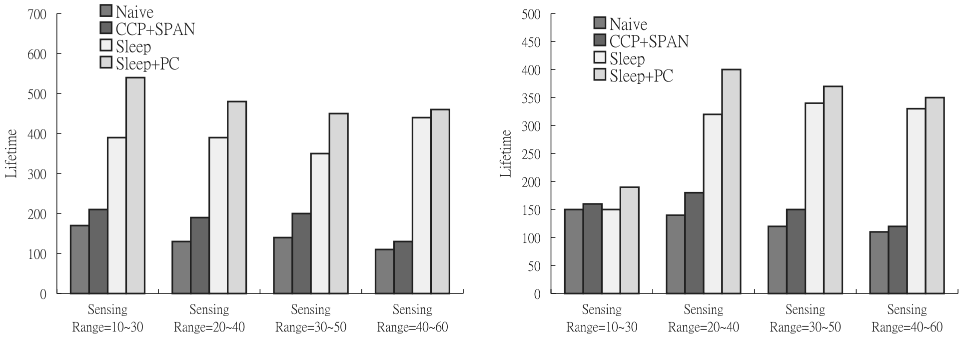


(a) ks = 2, kc = 1 (b) ks = 3, kc = 2

Fig. 15. Network lifetime under different communication ranges (sensing range = $15 \sim 25$).

Sleep+PC protocols can significantly reduce the rate that sensors fail. Overall, Sleep+PC performs the best. This can be explained by the levels of coverage and connectivity provided by a protocol, as shown in Figure 14(b) and Figure 14(c). There is too much redundancy in coverage and connectivity in both the naive and CCP+SPAN protocols. The Sleep protocol maintains the level of coverage pretty well, but the level of connectivity is still much higher than our expectation. Only Sleep+PC can maintain the best-fit coverage and connectivity levels. This justifies the usefulness of adopting power control to adjust the communication topology of the network. Figure 14(d) shows the network lifetime which is defined as the time before the levels of coverage and connectivity drop below our expectations. The lifetime of the naive protocol is around 150s. The lifetime of CCP+SPAN is around 200s. The Sleep and Sleep+PC protocols can significantly prolong network lifetime to around 340 and 410s, respectively. Figure 14(e), (f), (g), and (h) are from similar experiments where the goal is to maintain a 3-covered and 2-connected network. The trend is similar.

In the following, only the network lifetime is shown. Figure 15 shows the network lifetime under the same sensing range (15~25) but different communication ranges. In all situations, Sleep+PC performs the best. In fact, when the communication range increases, the gaps between Sleep+PC and other protocols enlarge relatively. So our power control scheme can effectively reduce network connectivity and prolong network lifetime. Basically, our schemes can perform better when sensors have larger communication ranges. This is because sensors with larger transmission ranges can find more neighbors, collect more necessary information needed for making sleeping and power-controlling decisions, and thus have a better chance of going to sleep and/or shrinking their powers. Besides, it is obvious that power control can more effectively reduce network connectivity if sensors' initial communication ranges are larger. However, how much Sleep+PC can outperform other schemes also relies on the network density and the level of coverage and connectivity to be achieved. If k_s and k_c are closer to k_{init}, our scheme is less effective. Figure 16 shows similar experiments under the same communication range (30~50) but different sensing ranges. In Figure 17, we further test under different



(a) ks = 2, kc = 1

(b) ks = 3, kc = 2

Fig. 16. Network lifetime under different sensing ranges (communication range $= 30 \sim 50$).

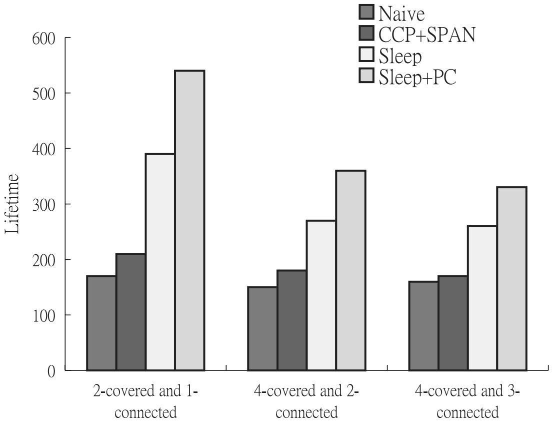


Fig. 17. Network lifetime under different coverage and connectivity requirements (sensing range $= 15 \sim 25$ and communication range $= 30 \sim 50$).

coverage and connectivity requirements. Around 1 to 2 times more lifetime can be demonstrated when comparing Sleep+PC to CCP+SPAN.

6. CONCLUSIONS AND FUTURE WORK

We have proposed fundamental theorems for determining the levels of coverage and connectivity of a sensor network. Earlier works are all based on stronger assumptions that the sensing distances and communication distances of sensors must satisfy some relations. We study this issue under an arbitrary relationship between sensing and communication ranges. Based on the proposed theorems, we have developed distributed protocols for determining the levels of coverage and connectivity of a sensor network and even for adjusting a sensor network to achieve the expected levels of coverage and connectivity. The approaches that we take are to put some sensors into the sleep mode and to reduce some sensors' transmission power. As far as we know, the combination of these mechanisms has not been well studied in this field, especially where coverage and connectivity issues are concerned. In our work, a deterministic model is used to formulate sensors' sensing and communication ranges. In reality, these values may follow a probabilistic model (such as a sensor's ability to successfully detect at object at a distance d with a probability $prob(d)$). The coverage connectivity combined issue still requires further investigation in this direction.

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