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保證無線感測網路中覆蓋及連結程度的分散式協定

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

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摘　　要

無線感測網路近年來受到眾多矚目，它是由許多價格便宜的感測器所組成，每一個感測器皆具有蒐集、儲存、及處理從環境中感測到的資料，並透過無線連結能和鄰近的感測器交換資訊。一個無線感測網路要能夠成功被應用在實際環境中，感測器必須要能同時能維持感測覆蓋率以及網路的連結性，這樣的研究議題已經在[24, 30]被提出來討論，在這兩篇論文中都達到相似的結論：只要感測器的通訊範圍不小於兩倍的感測範圍，那麼覆蓋程度同時也意味著相同的連結程度。而在這篇論文中，是從不同的角度來探討此議題，提出不依賴以上假設但是能夠同時保證無線感測網路之覆蓋性及連結性的必須及充要條件。這篇論文是我們先前論文[9, 10]的重要延伸，在先前的論文中描述了如何決定給定的感測網路之覆蓋程度，但是並沒有考慮到網路之連結性議題。這篇論文是第一個准許感測器的感測範圍及通訊範圍能夠是任意關係之研究，我們還利用提出來之同時保證無線感測網路之覆蓋性及連結性的條件發展出能夠決定，甚至進而調整網路中覆蓋性及連結性的分散式協定；當一個感測網路中有過多的感測器存在時，能夠調整無線感測網路之覆蓋性及連結性能夠延長網路的生命期，因此我們藉由讓一些感測器進入睡眠模式且調整通訊範圍來達到此目標。

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

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ABSTRACT

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 [24, 30], 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 paper, 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 [24, 30]. This work is also a significant extension of our earlier work [9, 10], 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.

Keywords: ad hoc network, coverage, connectivity, energy conservation, power control, sensor network, wireless network.

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Hsiao-Lu at CSIE, NCTU.

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Chapter 1

Introduction

The rapid progress of wireless communication and embedded micro-sensing 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 are connected by wire lines. Today, this environment is combined with the novel *ad hoc* networking technology to facilitate inter-sensor communication [16, 20]. 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 design of physical and medium access layers [19, 26, 29] and routing and transport protocols [3, 6, 8]. Localization and positioning applications of wireless sensor networks are discussed in [2, 17, 22].

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 [13, 14, 15, 23]. In [9, 10], the coverage problem is formulated as one of determining if a 2D/3D sensing field area is sufficiently *k-covered*, i.e., 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 [1, 21, 28]), 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 [27] 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 how long. Reference [5] 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 network connected is also a basic requirement of works targeted at *topology control*, which is to adjust sensors' transmission power for energy efficiency and collision avoidance [4, 12, 25].

In this work, we study the relationship between sensing coverage and communication connectivity of a sensor network. Reference [24] 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 meanwhile maintain communication connectivity is presented. If the communication ranges are less than twice the sensing ranges, [24] proposes to integrate CCP with SPAN [5] to provide both sensing coverage and communication connectivity. A similar result is also drawn in [30], 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 to cover the network.

It is clear that the results in [24, 30] are not applicable when some sensors' communication ranges are less than twice their sensing ranges even though others are not. Also, both [24, 30] assume that all sensors have the same sensing ranges. In this thesis, we relax these constrains 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 [24, 30] can be regarded as special cases of what proposed in this thesis. 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 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 of adjusting 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 emergency occurs, higher coverage and connectivity may be needed in an on-the-fly manner. For auto-configuration purpose, 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 adjustment 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 [9, 10], 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 sensor' sensing ranges is discussed in [31].

Some works also consider the coverage and connectivity issue, but have different assumptions or applications. Reference [18] considers a grid-based network consisting of sensors which may fail probabilistically and investigates the coverage, connectivity, and diameter of the network. Reference [11] studies the problem of minimizing energy consumption by suspending sensors' sensing and communication activities according to a Markovian stochastic process and meanwhile ensuring communication connectivity and sensing coverage. However, the definitions of "event coverage" and "path connectivity" distinguish from our goals. Given a spatial query requesting for data of interest in a geographical region, the goal of [7] 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 thesis is organized as follows. Chapter 2 gives some preliminaries. Several conditions for coverage and connectivity are presented in Chapter 3. Decentralized coverage-and-connectivity determination and adjustment protocols are developed in Chapter 4. Chapter 5 presents our simulation results. Chapter 6 draws our conclusions and future work.

Chapter 2

Preliminaries

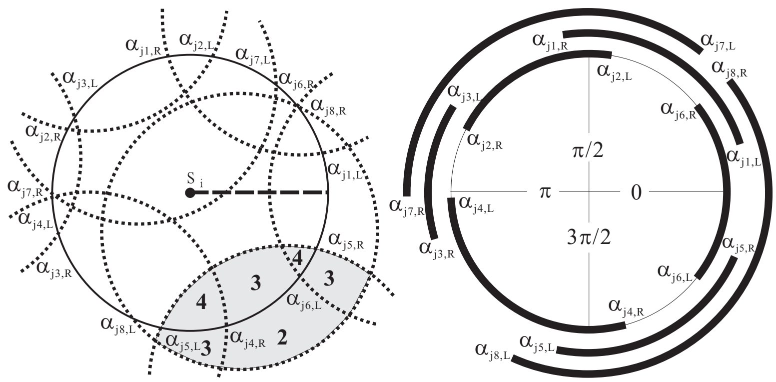
We are given a set of sensors, $S = \{s_1, s_2, \ldots, s_n\}$, in a two-dimensional area A. Each sensor s_i, $i = 1 \ldots n$, is located at a known coordinate (x_i, y_i) inside A and has a sensing distance of r_i and a communication distance of c_i. So, s_i can detect an object/event located within 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. However, unidirectional links are excluded, so packets can only be sent on bidirectional links.

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 concerned in our work and we assume the network is 1-covered at least. We formulate the general form of 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)

Figure 2.1: 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 [9], the coverage problem has been solved in an efficient way. Below, we briefly review the result, which will be used as a basis in our derivation.

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, i.e., 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 *[9] The whole network area A is k-covered iff 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 $[\alpha_{j,L}, \alpha_{j,R}]$, that 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, Fig. 2.1(a) shows how s_i is covered by its neighbors (shown in dashed circles). Mapping these covered angles in Fig. 2.1(b), it is easily to decide that s_i is 1-perimeter-covered.

Chapter 3

Conditions for Network Coverage and Connectivity

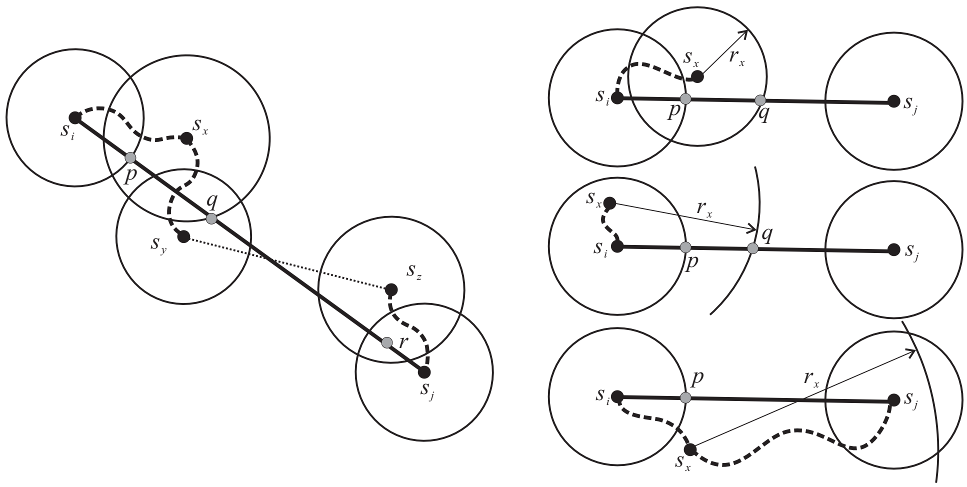
In this section, we propose theoretical foundations and necessary and/or sufficient conditions to solve the (k_s, k_c)-CC problem. We make no assumption on the relationship between r_i and c_i of sensor s_i. We show conditions for a sensor network to be k-covered and k-connected, and to be k-covered 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 has been proved useful to determine the coverage level of a sensor network in [9]. 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.

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 $N(i)$.



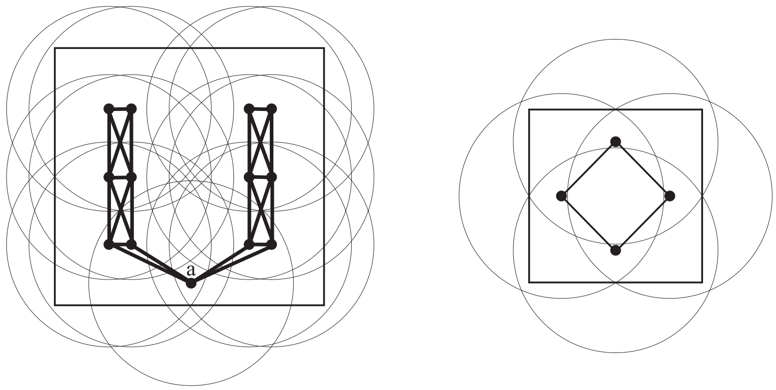
(a) (b)

Figure 3.1: Proof of Lemma 1: (a) the path construction, and (b) possible cases of s_x.

Note that the above definitions, though slightly different from what is defined in [9], would make possible deriving the following joint coverage-and-connectivity requirements on 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 Fig. 3.1(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. Fig. 3.1(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 the above argument until a sensor s_z is found which either covers s_j or intersect L at a point, say r, inside s_j's sensing range. In either case, there must exist a path between s_z and s_j, which proves this lemma. □



(a) (b)

Figure 3.2: 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.

Theorem 2 *A sensor network is k-covered and 1-connected iff 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. □

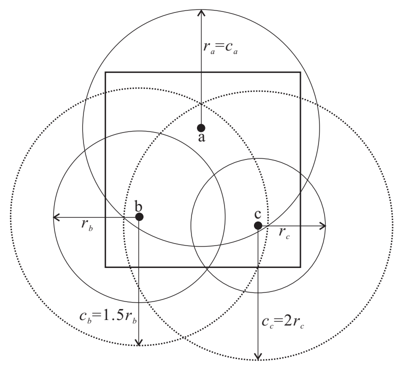


Figure 3.3: An example to compare Theorem 3 with results in [24, 30]. Solid circles and dotted circles are sensors' sensing ranges and communications ranges, respectively.

Below 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 Fig. 3.2(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. Fig. 3.2(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 [24, 30]. 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 [24, 30] can also be determined by Theorem 3. Furthermore, when the above assumption does not exist, Theorem 3 may still work while [24, 30] do not. For example, Theorem 3 can determine that the network in Fig. 3.3 is 1-covered and 1-connected, when some sensors' communication ranges are less than twice their sensing ranges.

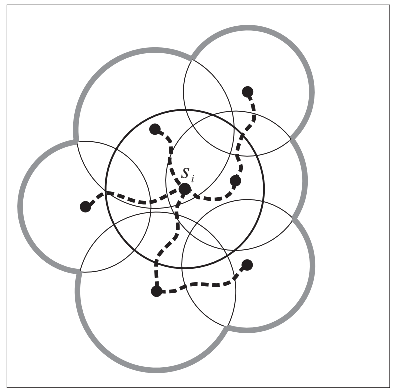


Figure 3.4: Proof of the Lemma 2.

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 *multi-hop neighboring set* of s_i, denoted as $MN(i)$, is the set of sensors each of which has a (single- or multi-hop) 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 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 $DN(i)$. 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

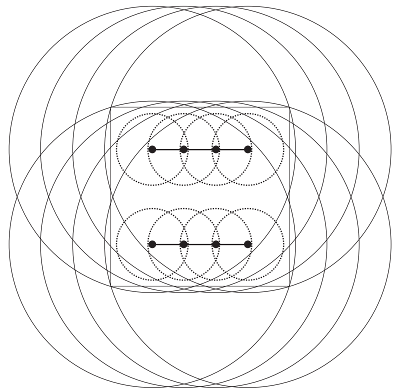


Figure 3.5: An example of two connected components each of which 1-covers A.

perimeter-cover s_i's perimeter and each has a path to s_i, as illustrated in Fig. 3.4. 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 iff 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 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 Fig. 3.5. Due to 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 such that no two components of the network are active at the same time.

Chapter 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 above 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 the above 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 above 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 [9]. 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 above level of coverage, k, is below our expectation, the sensor can flood a *QUERY* message to its neighbors to find out who else 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. By 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 the above 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 Fig. 3.2(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 subsection, 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. 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 which is a direct neighbor of s_x, then s_x is eligible to go to the sleep mode. Then s_x sends a *SLEEP* message to each of its neighbors and waits for their responses by setting up a timer T.

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 into sleep and to maintain synchronization, a sensor can have at most one pending grant at one time. Specifically, a *GRANT-SLEEP* message is clear from the pending status once a *CONFIRM/WITHDRAW* message is received (see step 4 below).

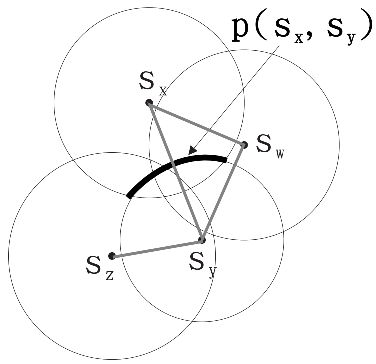


Figure 4.1: An example of the Sleep Protocol. Sensor s_x is a candidate with respect to sensor s_y.

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 expires, s_x broadcasts a *WITHDRAW* message to its neighbors.

Note that in the above step 1, s_x needs to know all direct neighbors of sensor s_y. Since s_x and s_y are direct neighbors, these sensors are s_x's two-hop neighbors. Fig. 4.1 shows an example of the above protocol. If s_x intends to go to sleep, it will check the perimeter $p(s_x, s_y)$ (shown in thick line). Since $p(s_x, s_y)$ 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 power control protocol is aim 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

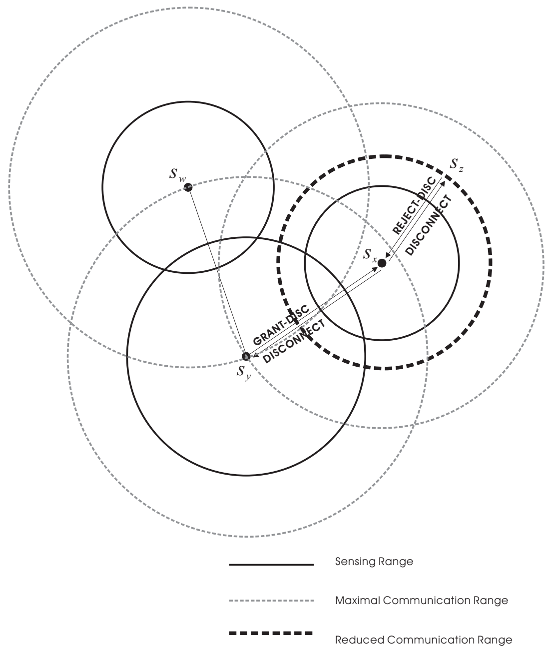


Figure 4.2: A power control protocol example.

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 sends a *DISCONNECT* message to s_y.

2. On receipt of s_x's disconnecting request, if s_y has no pending disconnecting request currently, s_y can reply 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.

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.

Note that in the above protocol, sensor s_y may not be able to reduce its transmission power even if s_x successfully receives s_y's granting message. This is because s_y may need to maintain connectivity with other neighbors that are farther away than s_x.

Fig. 4.2 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 the above 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 (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 Fig. 4.3, 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 sub-protocols are executed in that 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 up themselves, and one called T_{cycle} for sensors to re-check 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.

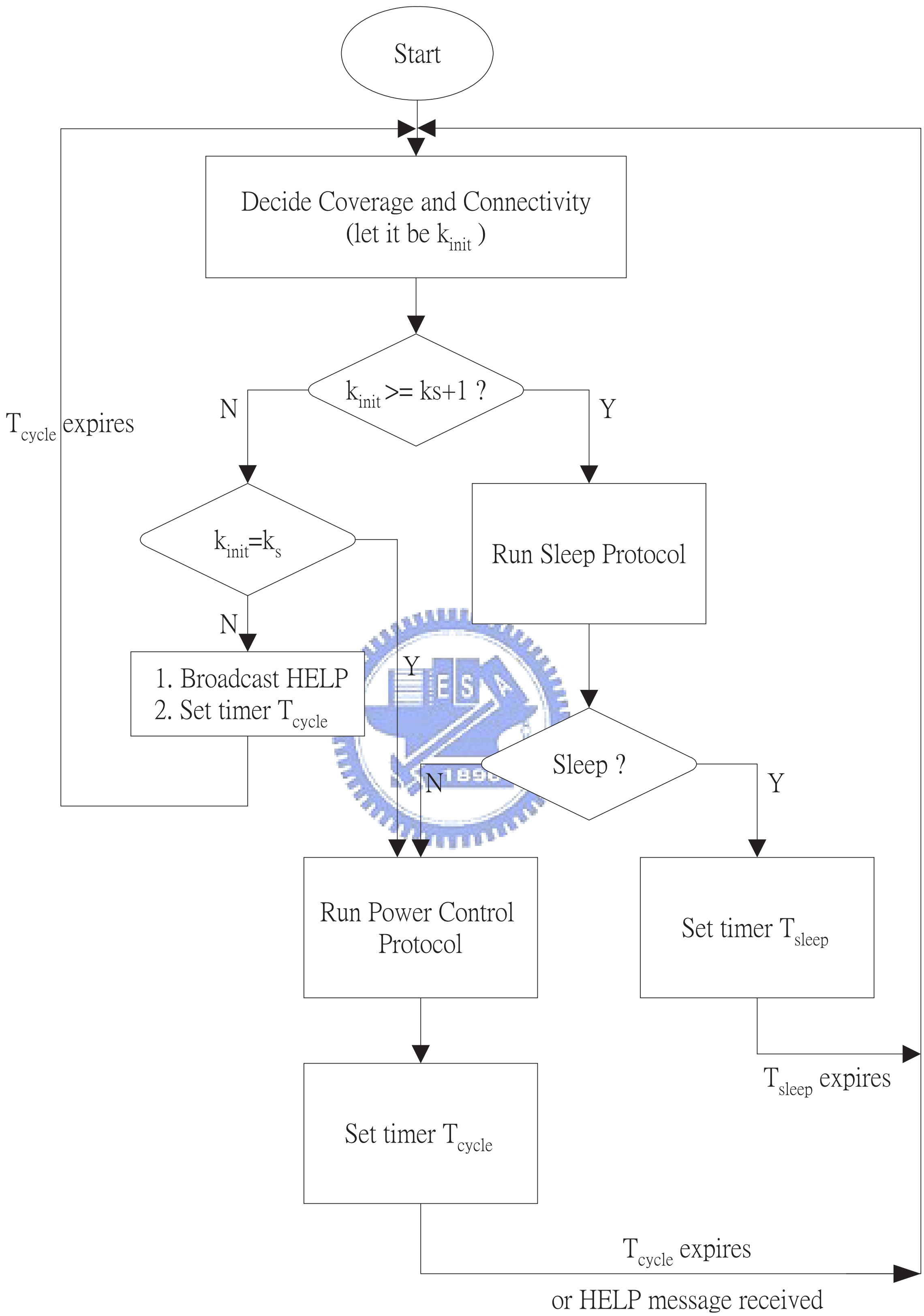


Figure 4.3: An integrated energy-saving protocol.

Chapter 5

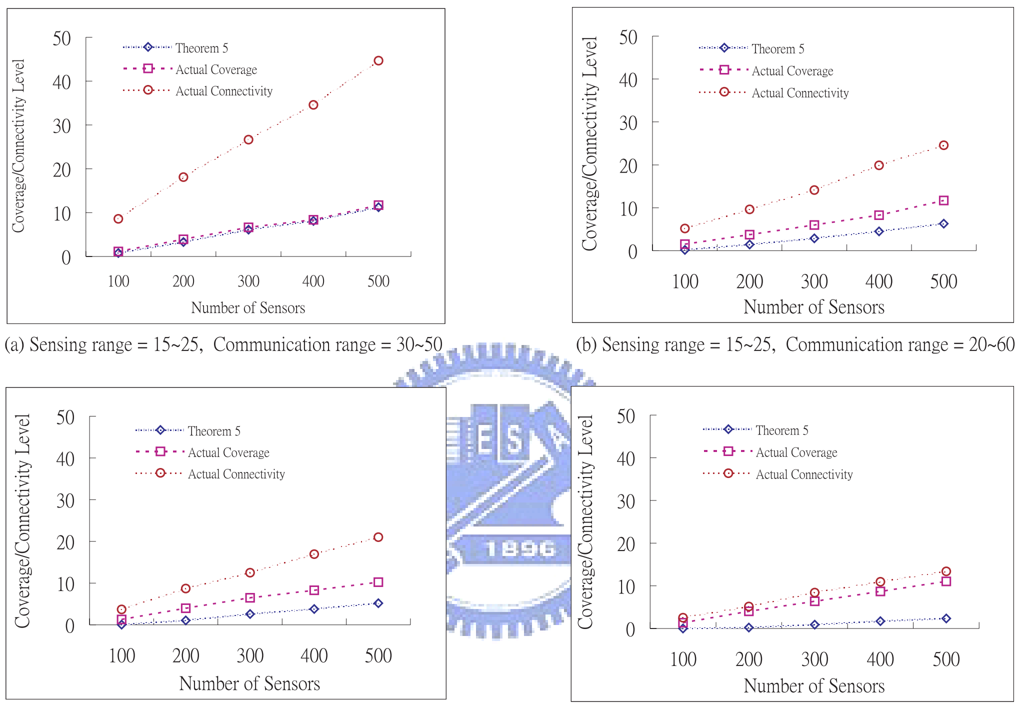
Simulation Results

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 100x100 square area, on which sensors are randomly deployed. The sensing range and communication range of each sensor are uniformly distributed in certain ranges.

Fig. 5.1 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 exhausted search. So Fig. 5.1(a) represents an ideal situation because what are found by Theorem 5 match closely with the actual values. The gaps increase as we move to Fig. 5.1(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 be able to know the existence of another sensors which have overlapping with its own sensing range if it only examines its direct neighbors. So a certain degrees



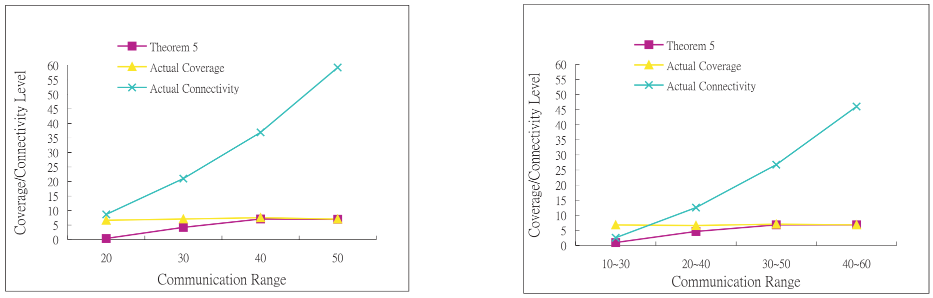
(a) Sensing range = 15~25, Communication range = 30~50

(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

Figure 5.1: Network coverage and connectivity under different communication ranges.



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

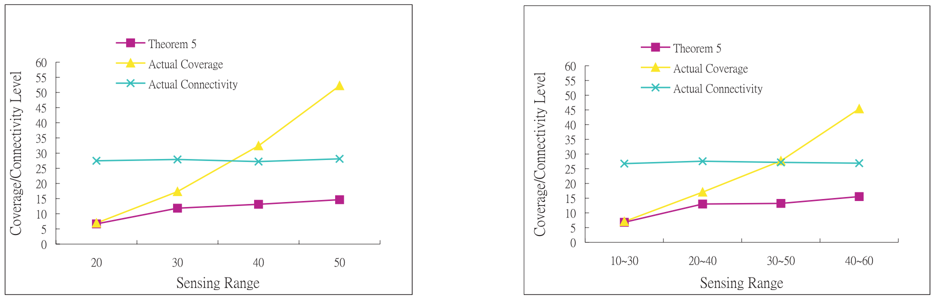
Figure 5.2: Network coverage and connectivity under different means and variations of communication ranges.

of coverage and connectivity are not discovered by Theorem 5.

Next, we keep the sensing ranges fixed, but change the communication ranges variations. Fig. 5.2 shows the coverage and connectivity in a 300-nodes network when we vary the mean and variation of communication ranges. Note that in each point of Fig. 5.2(a), sensors' communication ranges have no variation, while in each point of Fig. 5.2(b), the variation range is 20. As can be seen, although in both cases Theorem 5 finds about the same values of coverage and connectivity, since the actual connectivity reduces, Theorem 5 actually matches closer to the actual situations in the case of Fig. 5.2(b). In Fig. 5.3, we conduct the similar simulation by keeping the communication ranges unchanged but changing the mean and variation of sensing ranges. The trend is similar – Theorem 5 matches closer to the actual situations when there are larger variations in sensing ranges. Also, by comparing Fig. 5.2 and Fig. 5.3, we observe that the gaps reduce when the ratios of average communication range to average sensing range increase. The reason is that as the ratio increases, a sensor is able to collect more information about its neighborhood.

5.2 Experiment 2: Network Life Time

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 100x100 square area with sensing range = $15 \sim 25$, communication range = $30 \sim 50$, and initial energy = $8000 \sim 12000$ (all in a uniform distribution). Our goal is to achieve a k_s-

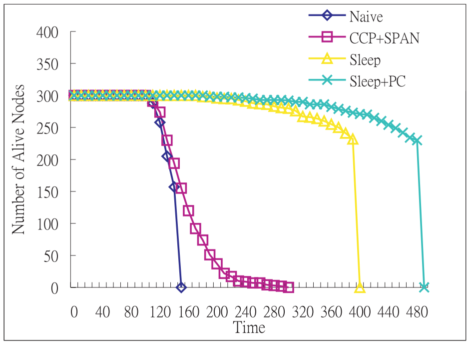


(a) Communication Range = 30~50 (b) Communication Range = 30~50

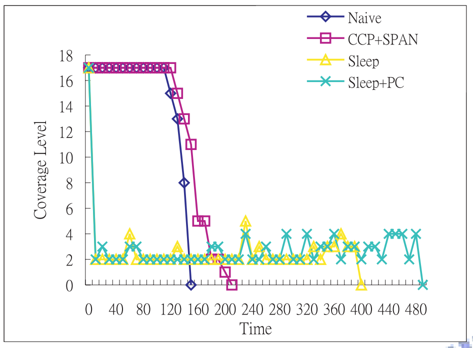
Figure 5.3: Network coverage and connectivity under different means and variations of sensing ranges.

covered and k_c-connected network. We sample the network status every 10 seconds. For each sensor, the energy consumed every second is proportional to the sum of its sensing range and communication range. 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 [24]. 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, [24] suggests to integrate 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.

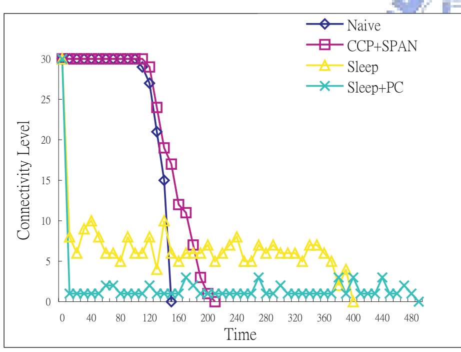
Fig. 5.4(a) shows the number of alive sensors when the goal is to maintain a 2-covered and 1-connected network. In the naive protocol, because nodes are always active, the number of alive sensors drops sharply at around 150 sec. Sensors in CCP+SPAN protocol fail at a slower speed. Both Sleep and Sleep+PC 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 Fig. 5.4(b) and Fig. 5.4(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



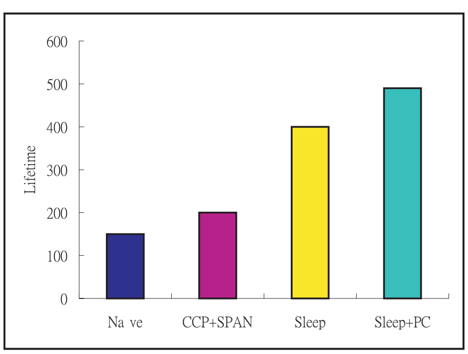
(a) $k_s = 2, k_c = 1$



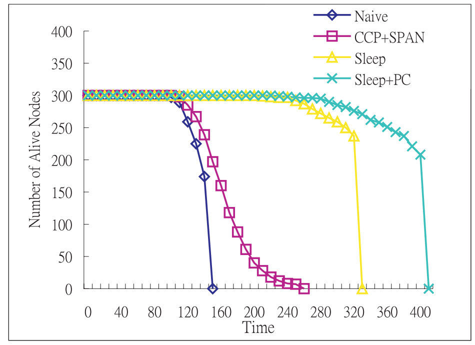
(b) ks = 2, kc = 1



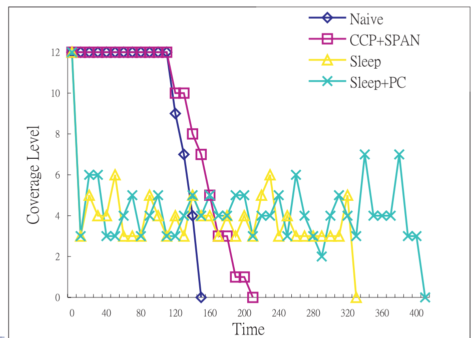
(c) ks = 2, kc = 1



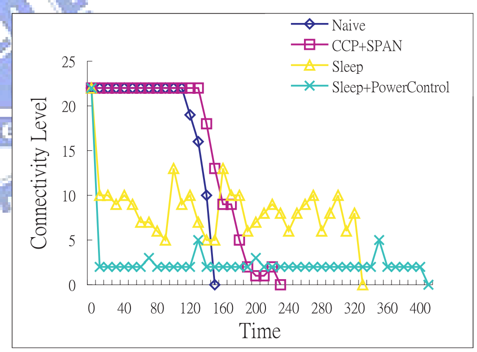
(d) ks = 2, kc = 1



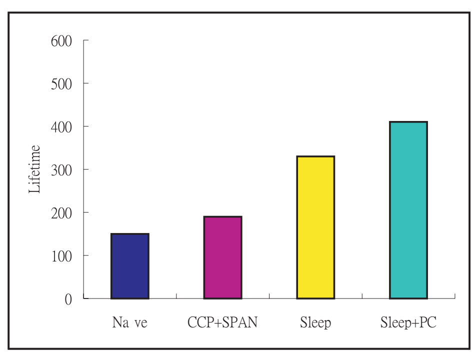
(e) ks = 3, kc = 2



(f) ks = 3, kc = 2

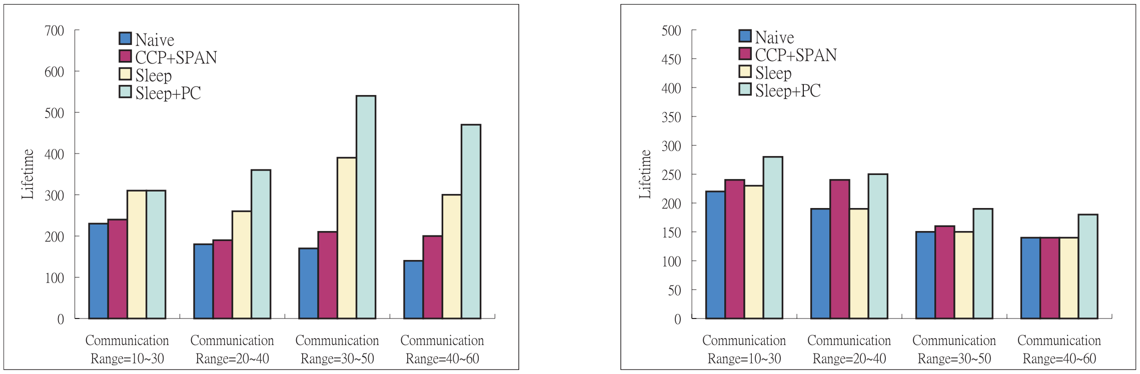


(g) ks = 3, kc = 2



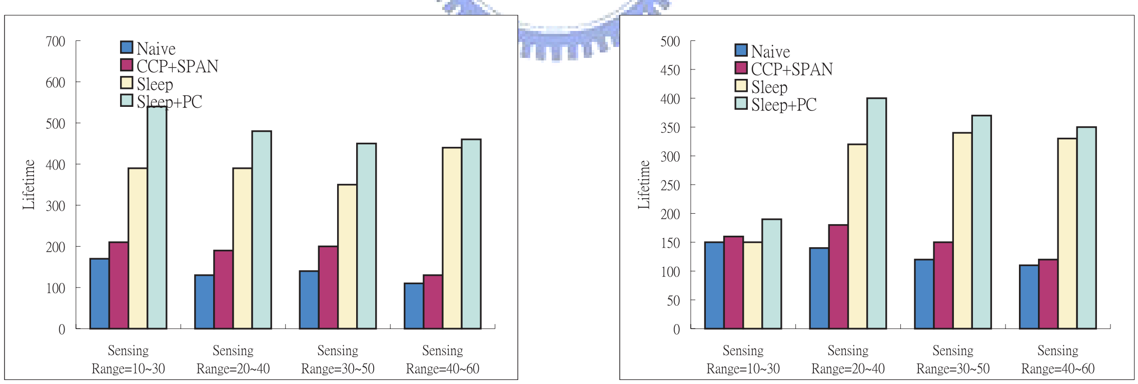
(h) ks = 3, kc = 2

Figure 5.4: Comparisons of the naive, CCP+SPAN, Sleep, and Sleep+PC protocols.



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

Figure 5.5: Network lifetime under different communication ranges (Sensing Range $= 15 \sim 25$).



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

Figure 5.6: Network lifetime under different sensing ranges (Communication Range $= 30 \sim 50$).

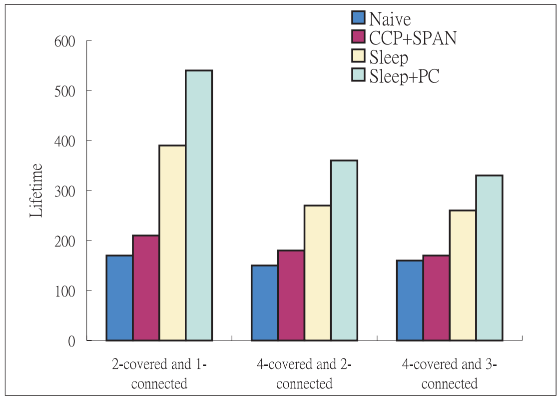


Figure 5.7: Network lifetime under different coverage and connectivity requirements (Sensing Range = 15 $\sim$ 25 and Communication Range = 30 $\sim$ 50).

control to adjust the communication topology of the network. Fig. 5.4(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 150 sec. The lifetime of CCP+SPAN is around 200 sec. The Sleep and Sleep+PC protocols can significantly prolong network lifetime to around 340 and 410 sec., respectively. Fig. 5.4(e), (f), (g), and (h) are from similar experiments when 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. Fig. 5.5 shows the network lifetime under the same sensing range (15$\sim$ 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 power control can effectively reduce network connectivity and prolong network lifetime, especially when communication ranges are relatively larger than sensing ranges. Fig. 5.6 shows the similar experiments under the same communication range (30 $\sim$ 50) but different sensing ranges. In Fig. 5.7, we further test under different coverage and connectivity requirements. Around 1 to 2 times more lifetime can be seen when comparing Sleep+PC to CCP+SPAN.

Chapter 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 when 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 can successfully detect an object in a distance d with a probability $prob(d)$). The coverage-connectivity-combined issue still requires further investigation in this direction.

Bibliography

[1] Z. Abrams, A. Goel, and S. Plotkin. Set K-cover algorithms for energy efficient monitoring in wireless sensor networks. In *Int'l Symp. on Information Processing in Sensor Networks (IPSN)*, pages 424–432, 2004.

[2] P. Bahl and V. N. Padmanabhan. RADAR: An in-building RF-based user location and tracking system. In *IEEE INFOCOM*, pages 775–784, 2000.

[3] D. Braginsky and D. Estrin. Rumor routing algorithm for sensor networks. In *ACM Int'l Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2002.

[4] M. Burkhart, P. von Rickenbach, R. Wattenhofer, and A. Zollinger. Does topology control reduce interference? In *ACM Int'l Symp. on Mobile Ad Hoc Networking and Computing (MobiHOC)*, pages 9 – 19, 2004.

[5] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *ACM/Kluwer Wireless Networks*, 8(5):481–494, Sep. 2002.

[6] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin. Highly resilient, energy efficient multipath routing in wireless sensor networks. *ACM Mobile Comput. and Commun. Review*, 5(4):11–25, Oct. 2001.

[7] H. Gupta, S. R. Das, and Q. Gu. Connected sensor cover: Self-organization of sensor networks for efficient query execution. In *ACM Int'l Symp. on Mobile Ad Hoc Networking and Computing (MobiHOC)*, pages 189–200, 2003.

[8] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocols for wireless microsensor networks. In *Hawaii Int'l Conf. on Systems Science (HICSS)*, 2000.

[9] C.-F. Huang and Y.-C. Tseng. The coverage problem in a wireless sensor network. In *ACM Int'l Workshop on Wireless Sensor Networks and Applications (WSNA)*, pages 115–121, 2003.

[10] C.-F. Huang, Y.-C. Tseng, and L.-C. Lo. The coverage problem in three-dimensional wireless sensor networks. In *IEEE Global Telecommunications Conference (Globecom)*, 2004.

[11] M. Inanc, M. Magdon-Ismail, and B. Yener. Power optimal connectivity and coverage in wireless sensor networks. Technical Report TR-03-06, Department of Computer Science, Rensselaer Polytechnic Institute, July 2003.

[12] N. Li and J. C. Hou. FLSS: A fault-tolerant topology control algorithm for wireless networks. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, 2004.

[13] X.-Y. Li, P.-J. Wan, and O. Frieder. Coverage in wireless ad hoc sensor networks. *IEEE Trans. Comput.*, 52(6):753–763, June 2003.

[14] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava. Coverage problems in wireless ad-hoc sensor networks. In *IEEE INFOCOM*, pages 1380–1387, 2001.

[15] S. Meguerdichian, F. Koushanfar, G. Qu, and M. Potkonjak. Exposure in wireless ad-hoc sensor networks. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, pages 139–150, 2001.

[16] G. J. Pottie and W. J. Kaiser. Wireless integrated network sensors. *Commun. ACM*, 43(5):51–58, May 2000.

[17] A. Savvides, C.-C. Han, and M. B. Strivastava. Dynamic fine-grained localization in ad-hoc networks of sensors. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, pages 166–179, 2001.

[18] S. Shakkottai, R. Srikant, and N. Shroff. Unreliable sensor grids: coverage, connectivity and diameter. In *IEEE INFOCOM*, pages 1073 – 1083, 2003.

[19] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless

sensor networks. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, pages 272–287, 2001.

[20] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie. Protocols for self-organization of a wireless sensor network. *IEEE Personal Commun.*, 7(5):16–27, Oct. 2000.

[21] D. Tian and N. D. Georganas. A node scheduling scheme for energy conservation in large wireless sensor networks. *Wireless Commun. and Mobile Comput. (WCMC)*, 3:271–290, 2003.

[22] Y.-C. Tseng, S.-P. Kuo, H.-W. Lee, and C.-F. Huang. Location tracking in a wireless sensor network by mobile agents and its data fusion strategies. In *Int'l Symp. on Information Processing in Sensor Networks (IPSN)*, 2003.

[23] G. Veltri, Q. Huang, G. Qu, and M. Potkonjak. Minimal and maximal exposure path algorithms for wireless embedded sensor networks. In *ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys)*, pages 40–50, 2003.

[24] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill. Integrated coverage and connectivity configuration in wireless sensor networks. In *ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys)*, pages 28–39, 2003.

[25] R. Wattenhofer, L. Li, P. Bahl, and Y.-M. Wang. Distributed topology control for power efficient operation in multihop wireless ad hoc networks. In *IEEE INFOCOM*, pages 1388 – 1397, 2001.

[26] A. Woo and D. E. Culler. A transmission control scheme for media access in sensor networks. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, pages 221–235, 2001.

[27] Y. Xu, J. Heidemann, and D. Estrin. Geography-informed energy conservation for ad hoc routing. In *ACM Int'l Conf. on Mobile Computing and Networking (MobiCom)*, pages 70–84, 2001.

[28] T. Yan, T. He, and J. A. Stankovic. Differentiated surveillance for sensor networks. In *ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys)*, pages 51–62, 2003.

[29] W. Ye, J. Heidemann, and D. Estrin. An energy-efficient MAC protocol for wireless sensor networks. In *IEEE INFOCOM*, pages 1567–1576, 2002.

[30] H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. In *NSF International Workshop on Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless, and Peer-to-Peer Networks*, 2004.

[31] H. Zhang and J. C. Hou. On deriving the upper bound of lifetime for large sensor networks. In *ACM Int'l Symp. on Mobile Ad Hoc Networking and Computing (MobiHOC)*, pages 121–132, 2004.

Curriculum Vita

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