Voronoi-Based Sleeping Configuration in Wireless Sensor Networks with Location Error

Xinyu Chen, Michael R. Lyu, *Fellow, IEEE*, and Ping Guo, *Senior Member, IEEE*

***Abstract*— In wireless sensor networks, to obtain a long network lifetime is a fundamental issue while without sacrificing crucial aspects of quality of service (area coverage, sensing reliability, and network connectivity). In this paper, we present a Voronoi-based sleeping configuration to deal with different sensing radii and location error. With our proposed sleeping candidate condition, redundant sensors are optionally identified and scheduled to sleep in order to extend the system lifetime while maintaining adequate sensor redundancy to tolerate sensor failures, energy depletions, and location error. Simulation results show that there is a tradeoff among energy conservation, area coverage, and fault tolerance, which varies between different sleeping candidate conditions.**

***Index Terms*— Wireless sensor network, Sleeping configuration, Voronoi, Location error**

I. Introduction

Wireless sensor networks are being increasingly deployed to perform certain tasks, such as sensing, tracking, measurement, and surveillance. Sensors, serving as nodes in this kind of network, are tiny power-constrained devices, which connect together through short-range radio transmission and form an ad hoc network. The monitoring and surveillance characteristics of a wireless sensor network require that every point in the region of interest should be sensed by the cooperation of deployed sensors; otherwise, an event occurring at under-monitored points will not be detected. This is the coverage issue, one of the fundamental measures for quality of service in wireless sensor networks.

To preserve the coverage requirement, the network should sustain a long lifetime without sacrificing the system's reliability. However, as wireless sensors are microelectronic devices, the energy source provided for them is usually battery power, which has not yet reached the stage for sensors to operate for a long time without recharging or replacement. Furthermore, the unattended nature of sensors and hostile sensing environments make manual battery recharging or replacement undesirable or impossible [1]. As a result, finding ways to prolong the functional lifetime both of individual sensors and of the network is an important challenge.

Besides the coverage problem, sensors may fail or be blocked due to physical damage or environmental interference. The failure of sensors may produce some void areas that do not satisfy the coverage requirement. Therefore, another important design issue is to sustain sensor network functionality without any interruption due to sensor failure; this is termed the reliability or fault tolerance (FT) issue [2]. Moreover, location error is introduced when the position of sensors cannot be engineered or predetermined with random deployment. Therefore, on the one hand, a sleeping configuration protocol should find as many sleeping-eligible sensors as possible to prolong network lifetime and to reduce packet collision; on the other hand, it should still retain enough redundancy to construct dependable sensor networks.

In this paper, we investigate Boolean sensing model (BSM) and propose Voronoi-based Sleeping Candidate Condition (VSCC) to evaluate the coverage of Voronoi vertices constructed by a sensor's one-hop neighbors, by which it decides whether itself is sleeping-eligible or not. After scheduling sleeping-eligible sensors, the constructed network remains connected in the presence of sensor's location error. Simulation results show that there is a tradeoff among energy saving, area coverage, and FT.

II. Related Work

Recently several sleeping configuration protocols have been proposed to address energy conservation and lifetime extension issues in wireless ad hoc sensor networks. Based on their adopted sensing model, they identified redundant sensors by means of geometric computations.

Tian *et al.* [3] proposed an off-duty eligibility rule based on sponsored sector (SS), which considers only the nodes whose distance is less than or equal to the sensing radius. This off-duty rule guarantees complete sensing coverage as long as no void area exists; however, the SS is an underestimation of sensing coverage provided by neighboring nodes and leads to excess energy consumption.

Jiang and Dou [4] improved the work of Tian *et al.* [3] by replacing communication neighbors with sensing neighbors, thus utilizing more coverage capability provided by neighbors. Nevertheless, their protocol may not preserve coverage when sensors have different sensing radii.

Yan *et al.* [5] introduced a differentiated surveillance service by calculating time reference point and time duration for each covered grid sampling point. The authors additionally provided FT by periodically broadcasting a heartbeat message; however, utilizing the heartbeat message to detect sensor failures is too energy-expensive in sensor networks.

Huang *et al.* [6] formulated the coverage problem as a decision problem. Whether a sensor is eligible to sleep is determined by observing how the perimeter of its sensing range is covered by its neighbors.

Xinyu Chen is with the Image Processing and Pattern Recognition Lab., Beijing Normal University, Beijing, China. xychen@bnu.edu.cn

Michael R. Lyu is with the Department of Computer Science and Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong. lyu@cse.cuhk.edu.hk

Ping Guo is with the Image Processing and Pattern Recognition Lab., Beijing Normal University, Beijing, China. pguo@bnu.edu.cn

Ye *et al.* [7] developed PEAS, a probing mechanism designed to conserve energy. The PEAS distributes node wake-ups randomly over time. In this solution, the application specified probing range indirectly determines the degree of coverage. However, this probing-based approach has no guarantee of adequate sensing coverage.

Voronoi diagram has also been investigated in the coverage problem of sensor networks. Based on Voronoi diagram, Meguerdichian *et al.* [8] formulated the coverage problem with maximal breach and maximal support paths to determine the best- and worst-case coverage for agents movement. The best-case coverage problem was solved by Li *et al.* [9] with efficient and distributed algorithms. However, the coverage definition in these two papers is somewhat different with ours. Carbunar *et al.* [10] and Zhang *et. al.* [11] utilized Voronoi diagram to detect the coverage boundary, which is a necessary condition in our developed criterion for selecting sleeping-eligible sensors.

III. Assumptions and Problem Formulation

To configure a sensor to sleep while preserving area coverage in a decentralized network environment, we should answer three fundamental questions: when we can assert that an area is covered by a set of sensors; what each sensor's responsibility is in providing area coverage; and whether its sleeping will produce any reduction on covered area.

Some general assumptions are introduced here to help us address these three questions. We assume that each sensor N_i knows its own location (x_i, y_i) [3], [12], [13], which can be obtained from the GPS or other localization systems. Initially, we assume that the obtained location information is accurate; however, this assumption will be relaxed in Subsection IV-B. Sensors are deployed in a two-dimensional constrained Euclidean plane; however, the argument can be easily extended to a three-dimensional space. Sensors can communicate directly with sensors within radius cr.

Definition 1: The one-hop communication neighbor set of sensor node N_i is defined by

$$N(i) = \{N_j \in \Omega \mid d(N_i, N_j) \leq cr, \ j \neq i\}, \qquad (1)$$

where Ω is the sensor set in a deployment region Φ and $d(N_i, N_j)$ denotes the Euclidean distance between sensors N_i and N_j.

A. Boolean Sensing Model

The Boolean sensing model (BSM) assumes that the sensing area of a sensor N_i is the disk with a radius sr_i centered at the location of the sensor itself [12], [14], and we call its sensing area the *sensing disk*, denoted as Ψ_i. Thus,

Definition 2: A measuring point y in a constrained deployment region Φ is defined as being covered if there is at least one sensor N_i whose distance to point y is less than its sensing radius sr_i, i.e.,

$$\exists N_i \in \Omega, \ d(N_i, y) < sr_i. \qquad (2)$$

In addition, we call the border of a sensor's sensing disk the *sensing perimeter*. If every measuring point in a deployment region is covered, we say that the deployment region is covered. Note that a sensor's sensing radius sr_i is different with its communication radius cr because different devices are involved [15]. As communication is usually bi-directional, the communication radius of all sensors are set the same. Although most sensor networks use homogeneous sensors with the same type [13], sensors may still employ different sensing radii due to manufacturing deviation.

B. Voronoi Diagram

Voronoi diagram, which is composed of a set of sensors, partitions a constrained two-dimensional sensor deployment region into a set of convex polygons such that all points inside a polygon are closest to only one particular sensor. These polygons are called Voronoi cells with finite areas as sensors are deployed in a constrained region. The boundary segment of a Voronoi cell is called the Voronoi edge shared by two sensors, and the intersection point of two Voronoi edges is called the Voronoi vertex shared by three or more sensors. The shared Voronoi edge of two sensors is on the perpendicular bisector line of a segment connecting these two sensors.

IV. Voronoi-based Sleeping Configuration

A sleeping sensor means its sensing devices and communication transceivers are turned off to save energy and to reduce packet transmission collision, i.e., it does not monitor its environment and does not send messages. As a result, the network topology will be changed and the field sensibility of some regions will be reduced. We define the initial *covered area* to be the percentage of the deployment region that satisfies the coverage requirement with randomly scattered sensors. If we can ensure that there is no reduction on covered area after a sensor goes to sleep and the constructed network backbone is still connected, we call this sensor a *sleeping candidate*. Otherwise, this sensor should keep working to provide its sensibility.

A. Sleeping Candidate Condition

All previous work [3], [12], [14] are based on the geometry calculation of the sensing disk. Inspired by the concept of coverage boundary introduced by Carbunar *et al.* in [10], in this subsection we develop a sleeping candidate condition with the property of Voronoi diagram. It evaluates the coverage of Voronoi vertices instead of the coverage of the sensing perimeters and the coverage of their intersection points.

Definition 3: A sensor N_i is on the boundary of coverage if there exists a point y on its sensing perimeter such that y is not covered by its one-hop working neighbors $N(i)$.

This definition considers only a sensor's one-hop and working neighbors but not all other sensors, which extends the corresponding concept in [10]. Therefore, it is more suitable to develop distributed and localized sleeping configuration algorithms. A theorem to evaluate whether a sensor is on the boundary of coverage or not is also provided in [10]:

Theorem 1: A sensor N_i is on the boundary of coverage if and only if its Voronoi cell is not completely covered by its sensing disk.

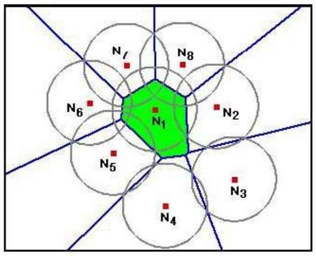

Fig. 1. Example of coverage boundary: N_1.

Fig. 1 gives an example of coverage boundary. For sensor N_1, all other sensors, N_i, $i = 2, \ldots, 8$, are its one-hop working neighbors. The small squares represent the locations of sensors, the circles are sensing perimeters, and the line segments are the Voronoi diagram constructed by these sensors. The outer rectangle is the constrained deployment region, thus each Voronoi cell is limited. As the sensing disk of N_1 does not cover its Voronoi cell, N_1 is on the coverage boundary. Obviously, if a sensor is on the coverage boundary, it is not sleeping-eligible as some parts of its sensing disk are only covered by itself and its sleeping will reduce the covered area. Thus, N_1 is not a sleeping candidate.

To facilitate the sleeping-eligibility evaluation process, we provide a corollary that can be easily derived from Theorem 1:

Corollary 1: A sensor N_i is on the boundary of coverage if and only if there exists one of its Voronoi vertices that is not in its sensing disk.

In principle, a sensor is a sleeping candidate if its sleeping does not reduce the covered area when it works. Therefore, if a sensor is on the coverage boundary, it cannot be sleeping-eligible. However, even if it is not on the coverage boundary, it may also not be sleeping-eligible. An example is that a sensor's sensing perimeter is all covered, but some inner parts of its sensing disk are only covered by itself. We need to provide a necessary and sufficient condition to evaluate a sensor's sleeping eligibility, which is provided as the following theorem.

Theorem 2: A sensor N_i is a sleeping candidate if and only if (1) it is not on the coverage boundary; and (2) when constructing another Voronoi diagram without N_i, all the Voronoi vertices of its one-hop working neighbors in N_i's sensing disk are still covered.

Proof: If sensor N_i is not on the coverage boundary, according to Theorem 1, its Voronoi cell is completely covered by its sensing disk, i.e., its Voronoi cell is in its sensing disk. As a result, in the regenerated Voronoi diagram without N_i, all vertices outside N_i's sensing disk are not changed, and no new vertices are generated outside N_i's sensing disk. This is because when removing a sensor, all the Voronoi cells of its neighbors will be enlarged. If all these Voronoi vertices are still covered, its neighbors should not become sensors on the coverage boundary due to N_i's sleeping. Thus no covered area is reduced. Therefore, N_i is a sleeping candidate.

For the "only if" part, if N_i is a sleeping candidate, (1) it is not on the coverage boundary, and (2) in the regenerated Voronoi diagram without N_i, all Voronoi vertices of its neighbors in N_i's sensing disk are still covered. First, let us assume that N_i is a sleeping candidate and it is on the coverage boundary. If a sensor is on the coverage boundary, parts of its sensing perimeter are only covered by itself. As a result, when N_i goes to sleep, these parts of its sensing perimeter are not covered by its neighbors, thus reducing the covered area. This leads to a contradiction. Second, let us assume that N_i is a sleeping candidate and one of those regenerated Voronoi vertices in N_i's sensing disk is not covered. As a uncovered Voronoi vertex is in N_i's sensing disk, this vertex is covered only by N_i if N_i is working. Therefore, N_i's sleeping results in this vertex being uncovered, i.e., N_i's sleeping reduces the covered area. This leads to a contradiction again. ■

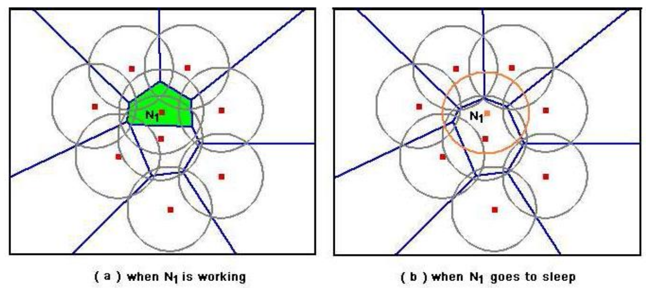

Fig. 2. Example of sleeping-eligible sensor: N_1.

Fig. 2 shows a sleeping-eligible sensor N_1. Fig. 2(a) displays when N_1 is working, it is not on the coverage boundary, and its Voronoi cell is completely contained in its sensing disk. Fig. 2(b) shows the regenerated Voronoi cell when N_1 goes to sleep. All the Voronoi vertices in its sensing disk are still covered by other sensors; therefore, N_1 is a sleeping candidate.

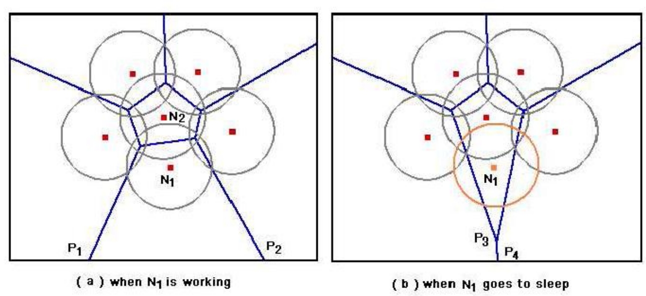

Fig. 3. Example of necessary condition: N_1.

The first condition that a sensor is not on the coverage boundary should be included as a necessary condition for the sensor to be sleeping-eligible, as illustrated in Fig. 3. If we evaluate N_1's sleeping eligibility only based on the second condition, N_1 is a sleeping candidate as no Voronoi vertex in its sensing disk is not covered, as shown in Fig. 3(b). However, we know that N_1 is not sleeping-eligible from

Fig. 3(a) as it is on the coverage boundary. The reason is that the first condition ensures that no Voronoi vertex outside a sensor's sensing disk would be changed due to the sensor's presence or absence. As a result, we can only evaluate the coverage of the Voronoi vertices in its sensing disk. As N_1 does not satisfy the first condition, it is easily observed from Fig. 3 that some old vertices, P_1 and P_2, outside the sensing disk of N_1 disappear, and some new vertices, P_3 and P_4, are generated. Fig. 3(a) also shows that sensor N_2 is not on the coverage boundary but it is not sleeping-eligible.

When a sensor utilizes all its one-hop working neighbors to calculate its sleeping eligibility, we get a 1-coverage sensor sleeping configuration. To obtain k-coverage, $k \geq 2$, we may divide its one-hop working neighbors into k mutually disjunct subsets. If a sensor satisfies the sleeping candidate condition (Theorem 2) with each subset of its neighbors, then we can say the sensor is a sleeping candidate for k-coverage.

The locally constructed Voronoi diagram with only one-hop neighbors may be an approximation to the Voronoi diagram generated by a centralized computation with the information of all deployed sensors. Our approach ignores the sensibilities contributed by one-hop out-of-reach sensors and so underestimates the coverage of a sensor's sensing disk by using partial sensor deployment information only. However, this underestimation is beneficial for building dependable wireless sensor networks, and reduces the overload on the network due to sleeping configuration. Therefore, the major computation incurred in this sleeping candidate condition is to calculate the Voronoi vertices generated by a sensor's one-hop neighbors. It can be solved in $O(n \log n)$, where n is the number of a sensor's one-hop neighbors. As this number is usually not very large, the resulted computational cost is also acceptable.

B. Location Error

In the aforementioned sleeping candidate condition, each sensor knows its accurate location. However, this is not realistic [16]. Here we assume that a sensor's obtained location is uniformly distributed in a circle located at its accurate position with radius ϵ_d. We call the ratio of the maximum location deviation ϵ_d to a sensor's sensing radius the *normalized deviation of location* ϵ, and the ratio of the distance between a point and a sensor to the sensor's sensing radius the *normalized distance* d. Without location error, when the normalized distance is less than 1, the point is deterministically covered by the sensor. Nevertheless, with location error, all points satisfying $d \leq (1+\epsilon)$ will be covered by the sensor with uncertainty.

Fig. 4 shows the coverage cases with different normalized distances, and Fig. 5 depicts the corresponding probability of coverage. In the former figure, a small solid circle denotes a sensor's obtained location, a dashed circle represents its normalized deviation of location ϵ, and a cross expresses the evaluated point. All points outside the outermost circle cannot be covered. If the sensor is located in the shaded region, the evaluated point can be covered. Therefore, the probability of coverage is the ratio of the area of the shaded region to the area of location deviation $\pi\epsilon^2$. Fig. 4(a.1) shows when $0 \leq \epsilon \leq 1$, all points in distance $(1-\epsilon)$ are still covered with probability 1; however, when $\epsilon > 1$, the maximum probability of coverage is $1/\epsilon^2$, as shown in Fig. 4(b.1).

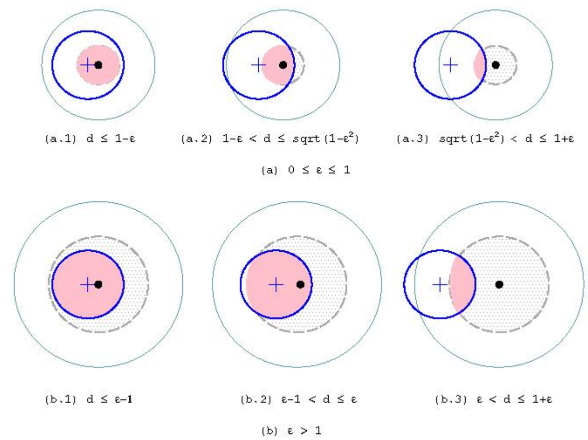

Fig. 4. Coverage relationship between a point and a sensor with location error.

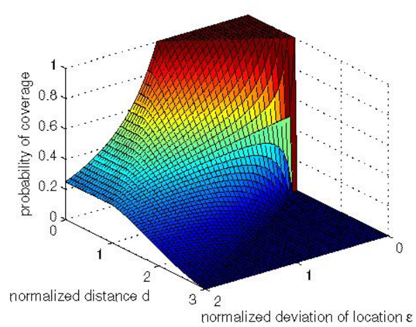

Fig. 5. Probability of coverage with location error.

With location error, after sleeping configuration we cannot ensure there is no loss of area coverage for the BSM; however, we can ensure that the uncovered area is less than a predefined threshold by reducing the sensing radii of deployed sensors during evaluation of sleeping eligibility. Given a normalized deviation of location ϵ and a predefined coverage probability, a sensor gets its maximized sensing distance from Fig. 5 and employs this sensing distance as its adjusted sensing radius.

C. Network Connectivity

When detecting an event, sensors report this event to data sinks. Therefore, the network should be connected to successfully perform its sensing and monitoring task. Considering only the sensibility issue when evaluating a sensor's sleeping eligibility may produce disconnected subnetworks, and as a result, even though an event is successfully detected by sensors, this information may not be delivered to the data sinks. To construct an effective sensor network, we must take the communication connectivity into consideration. For the BSM, a theorem has been proved [12], [14]: If the communication radius cr is at least twice of the maximal sensing radius sr, preserving area coverage implies maintaining network connected. However, it is only valid for accurate location information. Therefore, we evaluate whether a sensor's one-hop working neighbors will remain connected through each other when this sensor is removed. The connectivity check through a sensor's one-hop neighbors is heuristic, but simulation results show it performs well.

V. Simulations and Performance Evaluation

To evaluate and validate the capability of our proposed Voronoi-based Sleeping Candidate Condition for the BSM (VSCC), we have implemented them in NS-2 and conducted a simulation study.

A. *Configuration Protocols for Comparison*

According to the survey on coverage problems conducted in [17], we also evaluate as a baseline the performance of the sponsored sector (SS) eligibility rule proposed by Tian *et al.* [3] and Coverage Configuration Protocol (CCP) proposed by Wang *et al.* [12]. Both protocols are also based on the BSM. The SS rule considers only sensors inside the sensing radius of an evaluated sensor. The *CCP* determines a sensor's active eligibility by evaluating how the intersection points among sensing perimeters are covered inside the sensing disk of a considered sensor. To evaluate the effectiveness of these distributed protocols, we also construct a centralized algorithm with global coordination, denoted as *Central*, in which the same sleeping candidate condition as that of the *VSCC* is implemented.

B. *Parameters Setting*

The deployed sensing area is 50m×50m [3], [7], [14]. Sensors are scattered in this area with a uniform distribution. The default communication radius cr is 20m, the number of deployed sensors is 100, the required coverage degree is 1, and the normalized deviation of location error is 0, unless specified. We also assume that there is no packet loss during simulation. All the results quoted were obtained from an average of 20 simulation runs.

C. *Experimental Results and Discussions*

1) Sleeping Sensor vs. Communication Radius: Since the neighboring information is shared by broadcasting messages, the communication radius should affect the number of neighbors, and thus impact the percentage of sleeping sensors. Fig. 6 shows the variation of the percentage of sleeping sensors with the communication radius without and with location error. As the *SS* and the *VSCC* utilize one-hop neighbors, we also implemented the *CCP* with only one-hop neighbors for comparison.

When we increase the communication radius, a sensor will identify more adjacent sensors. If a sensor has more neighbors, its responsible sensing area is more likely to be covered by its neighbors. As a result, more sensors will be sleeping-eligible. However, if we increase the communication radius further, the performance of all the protocols tends to be saturated. In addition, without location error

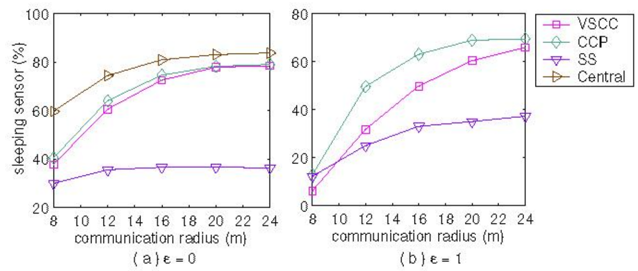

Fig. 6. Percentage of sleeping sensors vs. communication radius cr.

(Fig. 6(a)), the *SS* reaches saturation when $cr = sr$; for other protocols, the saturation condition is $cr = 2 \cdot sr$. This is because the *SS* only considers neighbors in the sensing radius of a sensor as its sensing sponsors. Although there are some other sensors providing sensing sponsorship, it ignores them, leading to lower percentage of sleeping-eligible sensors. The performance of the *VSCC* and the *CCP* are almost the same. With location error (Fig. 6(b)), all distributed protocols identify fewer sleeping-eligible sensors. Although the performance of the *CCP* is higher than those of other protocols, the cost it must to pay is higher loss of area coverage, which is shown in Fig. 7 later.

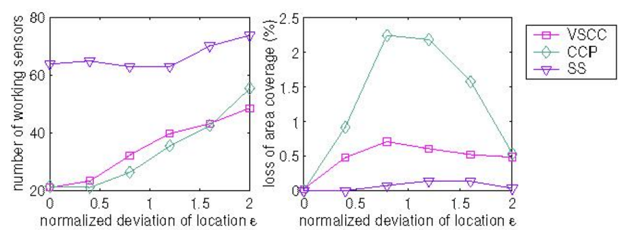

Fig. 7. Deviation of location.

2) Loss of Area Coverage: Fig. 7 shows the effect of location error on the loss of area coverage. With large deviations, fewer coverage sponsors are identified; therefore, the number of working sensors of all sleeping scheduling protocols increase with the normalized deviation of location. As the *SS* only considers coverage sponsors in a sensor's sensing disk, it keeps enough redundancy to tolerate location error, and its loss of area coverage is almost 0, as shown in Fig. 7(b). The *CCP* does not take the location error into consideration. Therefore, although its number of working sensors is the least when the normalized deviation of location is not very large, its loss of area coverage is the largest. The *VSCC*, on the other hand, reduce the loss of area coverage by allowing a few more sensors to work. It also performs well in tolerating location error. One interesting observation is that the loss of area coverage will be decreased when the normalized deviation of location becomes larger. This reduction is a result of more working sensors. Even when the number of working sensors in the *VSCC* is less than that in the *CCP*, the loss of area coverage in the *VSCC* is still less than that in the *CCP* with large deviation of location.

3) Sensitivity to Sensor Failures and Network Lifetime: To simulate failure due to causes other than energy depletion, such as destruction, malfunction, etc., we assume failures strike sensors according to an exponential distribution. The Mean Time to Failure (MTTF) is set between 1000s and 5000s.

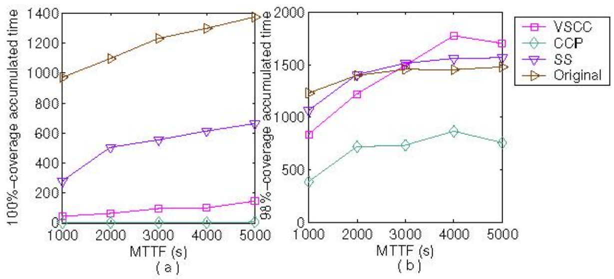

Fig. 8. χ-coverage accumulated time vs. MTTF when $\epsilon = 1$.

The simulation results are shown in Fig. 8 when the normalized deviation of location error $\epsilon = 1$. The data are given with the χ-*coverage accumulated time*, defined as the total time during which χ or more percentage of the original covered area still satisfies the coverage requirement. All χ-coverage accumulated times increase with the MTTF. If the original covered area should supply 100%-coverage as long as possible, the deployment of sensors should maintain as much redundancy as possible. Thus, the original deployment without sleeping configuration achieves the best performance, shown in Fig. 8(a). The underestimation of sleeping-eligible sensors in the *SS* makes it in an advantage to provide 100%-coverage under location errors and sensor failures. Although the *VSCC* take the location error into consideration, it still does not provide enough redundancy to tolerate sensor failures. Therefore, its performance in 100%-coverage is poor. The *CCP* almost cannot achieve 100%-coverage due to location error. When we decrease χ a little to 98%, the *VSCC* will perform comparably or even be superior to the *Original* and the *SS* when the MTTF increases. This can be explained by the extended system lifetime by sensor configuration. However, the *CCP* still does not provide acceptable performance.

VI. Summary

This paper exploits problems of energy conservation while maintaining desired coverage and network connectivity with location error in wireless sensor networks. We develop a Voronoi-based Sleeping Candidate Condition with the BSM (VSCC), which effectively identify redundant sensors for saving energy by exploiting the cooperation between adjacent sensors. Moreover, an adequate sensor redundancy is still kept to tolerate sensor failures and energy depletions. Finally, our sleeping candidate condition integrate the sensing coverage requirement with the network connectivity, which results in the network still being connected after sleeping-eligible sensors turn off their communication devices. Our results show that there exists a trade-off among network lifetime, sensing coverage, and FT.

VII. Acknowledgments

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