Journal of Harbin Institute of Technology (New Series), Vol. 15, No. 4, 2008

Coordinated node scheduling for energy-conserving in large wireless sensor networks

SHI Gao-tao, LIAO Ming-hong, XU Wen-xu
石高涛，　廖明宏，　徐文旭
(School of Computer Science and Technology, Harbin Institute of Technology, Harbin 150001, China, E-mail: kyle_shi@hit.edu.cn)

Abstract: Aiming at developing a node scheduling protocol for sensor networks with fewer active nodes, we propose a coordinated node scheduling protocol based on the presentation of a solution and its optimization to determine whether a node is redundant. The proposed protocol can reduce the number of working nodes by turning off as many redundant nodes as possible without degrading the coverage and connectivity. The simulation result shows that our protocol outperforms the peer with respect to the working node number and dynamic coverage percentage.

Key words: connectivity; coverage; node scheduling; energy efficiency; wireless sensor networks
CLC number: TP393　**Document code**: A　**Article ID**: 1005-9113(2008)04-0558-06

Recently, there has been a surge of interest in large-scale wireless sensor networks composed of many small, low-power devices with sensing, communication and limited on-board processing capability. It is expected that these networks will be deployed for various applications, ranging from the military to the civilian such as smart building, environment monitoring and biological detection[1-3].

In wireless sensor networks, nodes are operated on battery power, and energy is not always renewable due to cost, environmental and form-size concerns. This places a hard, stringent energy constraint on the design of the deployment and operation of these sensors, communication architecture, and the communication protocols. On the other hand, one important property of a sensor network is redundancy[2], which means that sensor networks are usually densely deployed. The high density can cause significant inefficiency problem leading to excessive power wastage. Variant sensor nodes may sense the same event and try to report it, increasing collisions by transmitting redundant data synchronously. Collisions require retransmissions and increase the unnecessary energy consumption. So it is desirable to minimize the number of nodes that remain active and schedule wireless sensors to be active and sleeping alternately in order to prolong the lifetime of the sensor.

However, without a wise consideration, alternating sensors between on and off (active and sleep) states inevitably generates blind points and consequently, reduces the network's coverage range and connectivity. Providing satisfactory connectivity and complete sensing coverage is critical requirement in sensor networks. Complete coverage is important for event detection because some information will be lost if some area are not covered. Satisfactory connectivity implies that event information detected by the nodes can be sent back to the sinks. Ideally, any active node should be able to communicate with any other active nodes (possibly using other active nodes as relays) and the area covered by unclosed nodes is not smaller than that which can be monitored by a full set of sensors. The two requirements make node scheduling more challenging.

An obvious, but important fact is that if the radio range is at least twice of the sensing range, a complete coverage of a convex area implies connectivity among the working set of nodes. This result was proved by Zhang[4] and Wang[5] independently. With such relationship, if the network is completely covered, the network is connected. So we can only focus on how to get complete covered networks with fewer active nodes.

1 Related Works

Minimizing energy consumption and prolonging the system lifetime has been a major design objective for wireless sensor networks. Except some energy efficient communication protocols[2], a lot of work has been focusing on the node scheduling. Due to the significant energy-saving when node is sleeping, a frequently used mechanism is to schedule the sensor node activity to allow redundant nodes to enter the sleep mode as often and for as long as possible.

Received 2006-09-22
Sponsored by the National Natural Science Foundation of China (Grant No. 60533110 and No. 90604013) and the Scientific Research Foundation of Harbin Institute of Technology (Grant No. HIT. 2002. 74).

Zhang and Hou[4] proved the relationship between the radio range and the sensing range and get the result that the full coverage can be obtained by optimally placing the subset of working nodes at the vertices of regular hexagonal plane tiling. Based on these results, authors proposed a distributed, localized algorithm, called optimal geographical density control (OGDC). This protocol attempts to select sensor nodes which are as close to optimal locations as possible to be working nodes. However, the algorithm can obtain approximate optimal result if and only if the network nodes are uniformly distributed. In fact, it can not guarantee complete coverage under the condition that the network is not uniformly.

Wang et al[5] generalized the result in Ref. [4] by showing that, when the communication range is at least twice the sensing range, a k-covered network will result in a k-connected network. The proof that a convex region is k-covered if it contains intersection points and all these intersection points are k-covered is also proved by the authors. A coverage configuration protocol is proposed which can dynamically configure the network to provide different coverage degrees requested by applications.

Tian et al[6] provide an algorithm that provides complete coverage using the concept of "sponsored area". After a sensor node obtains the position information from its neighbors, it calculates its sponsored area (defined as the maximal sector covered by the neighbor). If the union of all the sponsored areas of the sensor node covers the whole disk covered by it, it turns itself off. The work comes closest to ours, but only considers neighbors whose distance from the current node is not larger than the sending range and so can not minimize the active nodes. And its rule can not apply to the neighbor who lies out of the sensing range as the discussion below. At the same time, Tian did not take connectivity into account.

Ye[7] proposed a probing-based density control protocols by maintaining a subset of node in working state to ensure desired sensing coverage and others are allowed to fall asleep. A sleeping node wakes up at an inconstant frequency to probe its local neighbor and starts working only if there is no working node in its vicinity. The algorithm does not guarantee complete coverage.

Xu et al[8] and Santi et al[9] both proposed an algorithm which divides the region into virtual rectangular grids and keeps only one node staying at active in each grid. Although the protocol can maintain coverage by adjusting the maximum distance between the adjacent, the author did not consider the problem.

In addition, Huang and Tseng[10] presented a solution to determine whether a sensor networks is k-covered but didn't mention how to schedule the nodes and give some optimizations as in our work. In Ref. [11], the authors investigate linear programming techniques to optimally place a set of sensors on a sensor field (three dimensional grid) for a complete coverage of the field. Meguerdichian et al[12] consider a slightly different definition of coverage and address the problem of finding maximal paths of lowest and highest observabilities in a sensor network.

In this paper, we only consider 1-coverage such as Refs. [4], [6] and [8]. Our work is based on the same assumption as Ref. [4] and inspired by Ref. [6] but provides a different solution. Compared with the work in Ref. [6], the proposed protocol can reduce the number of working nodes to the maximum extent without degrading the coverage and connectivity.

2 Coordinated Node Scheduling

In this subsection, we address the problem of constructing a connected 1-coverage networks with fewer active nodes. We assume that all nodes lie on a 2-dimensional plane and a sensor's sensing range is a circular area centered at this sensor with a radius of R_s. The radius of the circle is known as the coverage radius. Also, we assume that, for each node, the radio transmission range R_c is at least twice of the sensing range R_s so that we can only focus on constructing a compete coverage network while it is connected.

2.1 Preliminaries

To facilitate later discussion, we introduce the following definitions and notations.

Definition 1 (Neighbor) Given a sensor network consisting of a set of sensors Φ, the neighbor set of node $i \in \Phi$ is defined as $N(i) = \{j \in \Phi \mid d(i, j) \leqslant R_c,\ i \neq j\}$, where $d(i, j)$ denotes the distance between node i and j. We notate the neighbor set which lies in the $2R_s$ range and that in R_s range of node i by $N_{2s}(i) = \{j \in \Phi \mid d(i, j) \leqslant 2R_s,\ i \neq j\}$ and $N_s(i) = \{j \in \Phi \mid d(i, j) \leqslant R_s,\ i \neq j\}$ respectively.

Obviously, if $R_c \geqslant 2R_s$, $N_{2S}(i) \subseteq N(i)$. In this paper, the definition of neighbor is more comprehensive than that in Ref. [6] in which Tian only considers the nodes within sensing range as neighbor.

Definition 2 (Sensor Covering a Point, Area A is covered): A point p in area A is said to be covered by i if it is within i's sensing range, i.e. $d(p, i) < R_s$. Notated as cover(i, p). Area A is covered if and only if every point in A is covered by at least one sensor.

Definition 3 (Redundant node and backbone node). Let S_i be the sensing area of sensor i. If for all $j \in N_{2s}(i)$, $\bigcup S_j \supseteq S_i$, sensor i is called redundant node. Otherwise, sensor i is called backbone node.

Given a node i, for each $j \in N_{2s}(i)$, S_i and S_j touch at point P_{j1} and P_{j2} arranged in the counterclockwise order as illustrated in Fig. 1. Let $\angle P_{j2}ij = \angle jiP_{j1} = \omega_{ij}$. The sector, bounded by segment iP_{j1}, iP_{j2} and inner arc $P_{j1}P_{j2}$, is called sponsored sector by node j to node i, just as the definition in Ref. [6]. The direction of node j referred to node i is denoted as θ_{ij}. Here, ω_{ij} lies in $[0, \pi/2)$ and θ_{ij} in $[0, 2\pi]$. Considering two sensors i and j located in positions (x_i, y_i) and (x_j, y_j) respectively, ω_{ij} and θ_{ij} can be easily obtained. Note: $\omega_{ij} = \omega_{ji}$ but $\theta_{ij} \neq \theta_{ji}$. The definition of ω_{ij} is also different with that in Ref. [6].

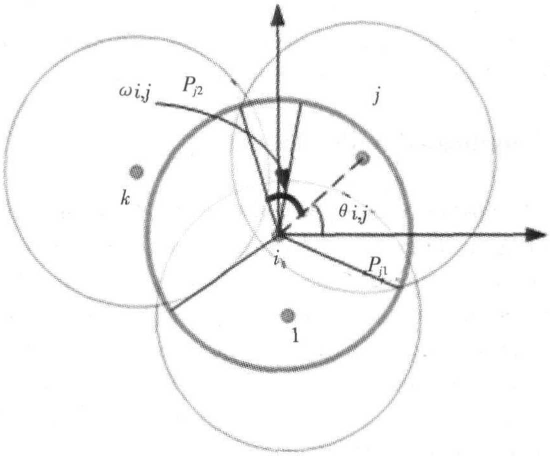


Fig. 1 Redundant node judgment model

Define the operations between ω_{ij} and θ_{ij} as

$$\theta_{ij} \odot \omega_{ij} = \begin{cases} \theta_{ij} - \omega_{ij} & \text{if} \quad \theta_{ij} - \omega_{ij} \geqslant 0, \\ 2\pi + \theta_{ij} - \omega_{ij} & \text{otherwise} \end{cases} \tag{1}$$

$$\theta_{ij} \oplus \omega_{ij} = \begin{cases} \theta_{ij} + \omega_{ij} & \text{if} \quad \theta_{ij} + \omega_{ij} \leqslant 2\pi, \\ \omega_{ij} + \theta_{ij} - 2\pi & \text{otherwise} \end{cases} \tag{2}$$

Further, let

$$[\alpha, \beta] = \begin{cases} [[\alpha, \beta]], & \alpha \leqslant \beta \\ [0, \beta] \cup [\alpha, 2\pi], & \alpha > \beta \end{cases} \tag{3}$$

2.2 Scheduling Rule

According to Definition 3, if a node is redundant, the area covered by it will still be covered when the sensor node is turned off. So if we can judge which sensor is a redundant node, the node can operate at sleeping state without destroying the coverage. In this section, based on the following theorem in Ref. [4], we gradually deduce the scheduling rules using node location.

Theorem 1[4] Suppose the size of a disk is sufficiently smaller than that of a region R. If one or more disks are placed within the region R, and at least one of those disks intersect another disk, and all crossings in the region R are covered, then R is completely covered.

By Theorem 1, if a region is lager enough and every node coverage areas intersect one another with all crossings are covered, the region is completely covered. So, if one node is turned off and the region is kept covered, we predicate that it is redundant node. However, in distributed networks, determining whether a point is covered or not is not an easy work. Even though, Theorem 1 does give us a hint for determining whether a node is redundant.

Theorem 2 A Region R is complete covered if and only if for any node i and its neighbor j, they satisfy condition:

$$\left(\bigcup_{j \in N_{2S}(i)} [[\theta_{ij} \odot \omega_{ij}, \theta_{ij} \oplus \omega_{ij}]]\right) = [0, 2\pi] \tag{4}$$

Proof $[[\theta_{ij} \odot \omega_{ij}, \theta_{ij} \oplus \omega_{ij}]]$ represents the central angel of sponsored sector by node j to node i. In view of the relationship between the central angle and arch, the points in the minor arch of $P_{j1}P_{j2}$ are completely covered by the node j. So if the Eq. (4) holds, it is confirmed that the perimeter of the covered range by node i is completely covered by i' s neighbor nodes. So when all the nodes in region R and its neighbors satisfy the condition, by Theorem 1, the region is completely covered. In reverse, when the region is complete coverage, the perimeter of each node' s sensing range should be completely covered by its neighbor nodes. So, for any node i, Eq. (4) holds.

From the above proof, we can see that Theorem 2 is the equivalent of Theorem 1. According to the Theorem 2, if we turn off a node i and the rest are still has the attribute presented by Eq. (4), node i is redundant. However, Theorem 2 assume that the region is infinite large and so has no boundary effect. In the reality, the node located at edge will not be true of the above condition but its neighbor is still redundant. So we are now in the position to discuss how to eliminate the boundary effect and give the scheduling rule in real case.

Theorem 3 Node i is redundant if for any neighbor node $j \in N_{2s}(i)$, it satisfies the condition that

$$\left(\bigcup_{k \in N_{2S}(j) \wedge k \neq i} [[\theta_{jk} \odot \omega_{jk}, \theta_{jk} \oplus \omega_{jk}]]\right) \supseteq [[\theta_{ji} \odot \omega_{ji}, \theta_{ji} \oplus \omega_{ji}]] \tag{5}$$

Proof The right part of expression (5) represents the circle segment covered by node i to node j. Therefore, when the expression (5) is true, the segment covered by node i will still be covered by the union of other neighbors of node j after turning off node i. By Theorem 1, when turning off node i, the original area covered by node i is still be covered. The result is as follows.

Theorem 4 Node i is a redundant node if node i and its neighbor node $j \in N_s(i)$ satisfy the condition

$$\left(\bigcup_{j \in N_s(i)} [[\theta_{ij} \odot \omega_{ij}, \theta_{ij} \oplus \omega_{ij}]]\right) = [0, 2\pi] \tag{6}$$

Proof Let F_{ij} be the area of the sponsored sector by node j to node i. The overlapping area of node i and node j is $S_i \cap S_j$. By Eq. (6), we have $\bigcup_{j \in N_S(i)} F_{ij} = S_i$. Moreover, it is true that $\left(S_i \cap S_j\right) \supseteq F_{ij}$ because $d(i,$

$j) \leqslant R_s$. Then we have $\bigcup_{j\in N_S(i)} \left(S_i \cap S_j\right) \supseteq S_i$, thus $\bigcup_{j\in N_S(i)} \left(S_i \cap S_j\right) = S_i$ which means that node i's sensing area is completely covered by its neighbors.

We note that Theorem 3 resembles that in Ref. [6], but it is just a special case when considering node redundancy.

Theorems 3 and 4 present the criteria for determining whether a node is redundant or not in real case if the nodes in the networks can get the neighbor's location information.

Observation 1 A very obvious fact is that if node i is redundancy, there is at least one neighbor who is in the sensing range of node i. This can be used to optimize the schedule algorithm.

2.3 Scheduling Protocol

In the proposed protocol, each node in the networks periodically makes decision on whether to turn on or off itself using local neighbor information. By local, we mean that every node only needs the information about its one-hop neighbors, more precisely, the neighbor within its twice sensing range. The message kind and its meaning are listed in Tab. 1. A node may be in one of three states: Sleep, Active, and Back-off. The protocol runs in round and at the beginning of every round, all the nodes are in Active state. In what follows, we give the detailed description of the actions taken by a node in every round.

Tab. 1 Type and meaning of message in protocol

Name of message	Abbreviate	Meaning of message
Hello Message	HMsg	Report node information about its position
Try-to-Sleep Message	TSMsg	Request to sleep
Sleep Message	SMsg	Notify its neighbor it switch into Sleep state
Response Message	RMsg	Notify the try-to-sleep node that it can not sleep

S1. Every node broadcasts a Hello Message (HMsg) including its position and ID. All its neighbors store this information.

S2. If the active neighbors of node i are all more than Rs away from node i, node i will always be in Active state.

S3. If node i and its active neighbors within sensing range Rs make equality (6) true, node i broadcast a Sleep Message (SMsg) and switches its state from Active to Sleep.

S4. If node i is still in Active state after S3, it broadcasts a Try-to-Sleep Message (TSMsg) firstly and then waits the responses from it neighbors for a short period time T_w. Each active neighbor in $N_{2s}(i)$ determines whether the expression (5) is true. If false, the neighbor sends a Response Message (RMsg) to node i. Otherwise, it keeps silent. If node i do not receive any RMsg after T_w, it switches state from Active to Sleep. Otherwise, it remains active.

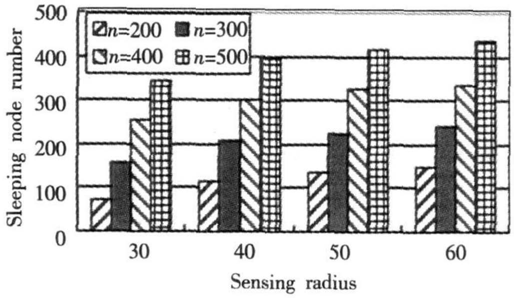
In order to avoid the blind point problem, the back-off mechanism should be introduced. Its basic idea is that when a node finds that it is redundancy and ready to sleep, it enter into Back-off state and set a back-off time of period T_d during which it will switches to Sleep state if it has not received any other Sleep Message. If the node receives some Sleep Message during the period, it re-evaluate whether it should turns off after updating the sender's information. In order to balance the energy consumption, T_d should be directly proportional to the residual energy of the node ready to sleep so that the more the residual energy is, the more likely the node work in this round.

3 Simulation Results

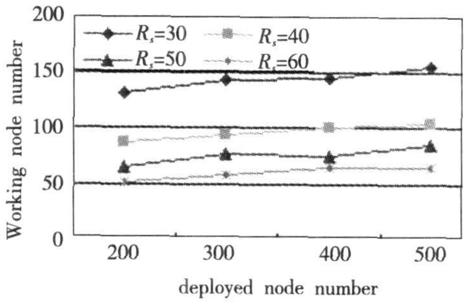
In this section, we present the result of simulations that we ran to compare the protocol algorithms with the exiting algorithms presented in Ref. [6] which we call DT protocol. Although CCP[5] is superior to DT and OGDC[4] is shown to perform better than CCP in some cases, CPP incurs higher computational complexity and OGDC can not guarantee complete coverage under the condition that the network is not uniformly. So we only provide the results compared with DT. We are interested in the working node number and the coverage percentage after the scheduling process completes. We ran the simulation on randomly generated sensor networks where in a certain number of sensor nodes are placed randomly in an area of 200 × 200 unit square. Each sensor has a uniform sensing radius varying from 20 to 50 units. Each data point reported below is an average of 5 simulation runs unless specified.

3.1 Working Node and Sleeping Node

We vary the deployed node number from 200 to 500 in the same area to investigate the relationship between the number of working nodes and the sleeping nodes versus the number of deployed node and node sensing radius. The results are illustrated in Fig. 2. From Fig. 2(a) we can see that increasing the number of the deployed nodes and increasing the sensing radius will bring on more nodes being turned off. However, as shown in Fig. 2(b), the number of working nodes increases as the deployed node number increasing when the sensing range remains constant. This is due to the boundary effect which induces the node located at the edge of the region not to be turned off. Even though, the curves in Fig. 2(b) show that our protocol still effectively limits the number of working node.



(a) sleeping node vs deployed nodes



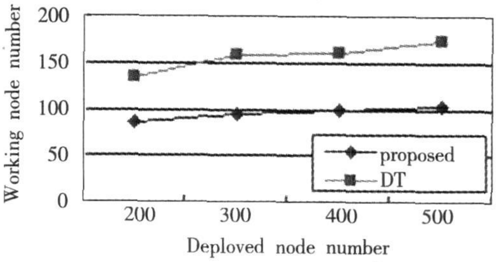
(b) working node vs deployed nodes

Fig. 2 Sleeping nodes number and working nodes number versus deployed node number with different sensing radius

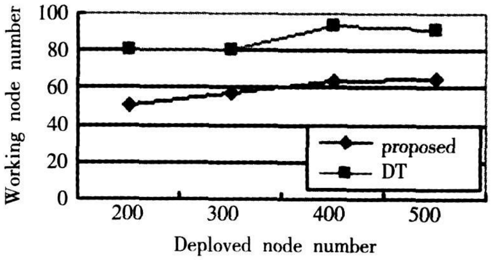
Fig. 3 compares the number of working nodes achieved by the proposed protocol and that presented in Ref. [6] when the deployed nodes number increases from 200 to 300 and the sensing radius is set to 40 and 60 units. We focus the effectiveness of limiting the number of working nodes. As shown in Fig. 3, our algorithm excels the DT all the time. In fact, the average number of working nodes is up to 65% less than that achieved by DT when the sensing radius is 40 units. When the sensing radius increases to 60 units, the average number of working nodes achieved by DT is 50% more than that of ours. The decrease from 65% to 50% is due to the increasing of neighbors in Rs range as the sensing radius increasing and the probability of being covered by its neighbors in Rs range increases.

3.2 Dynamic Coverage Percentage

In order to achieve the coverage percentage, we divide the area into 200 × 200 square grids. A grid is considered covered if the center of the grid is covered. Assuming all the nodes are active, we can get the total number of grids covered by the initial network, denoted by $C(0)$. Then the scheduling algorithm is applied and the total number of grid covered by active sensors are counted, denoted by $C(t)$. The instantaneous area coverage ratio is estimated by $C(t)/C(0)$. We use the energy model in Ref. [16] where the power consumption ratio for transmitting : receiving (idling) is 5 : 1. We define one unit of energy as that required for a node to remain idle for 1 s. Each node has a sensing radius of 20 unites and a lifetime of 1000 s if it is idle all the time. Each node broadcasts a message with probability $p = 0.5$ within 1 s. In theory, the average energy consumption of a active node in 1 s is $p \times 5 + (1 - p) \times 1 = 3$ units. So the lifetime of a single node is $1000 \div 3 = 333$ s.



(a) Sensing radius $R_s = 40$



(b) Sensing radius $Rs = 60$

Fig. 3 Number of the working nodes versus number of sensor nodes

Fig. 4 provides the result of dynamic coverage rate. Firstly, we can see that the first few sensor deaths for the new protocol and DT happen at roughly the same time. This is because some sensors never have the chance to be turned off due to the initial deployment regardless of the scheduling algorithm. Secondly, the two algorithms both prolong the lifetime compared to that of all nodes being active all the time. However, the time taken by the new algorithm for the coverage percentage to below 80% is a little longer than that of DT (362 s and 334 s respectively). Furthermore, the proposed protocol has a more graceful degradation of area coverage ratio compared to DT. Under the DT schedule the coverage ratio decreases sharply after 330 s while the new protocol can still provide a comparatively high coverage ratio about 66.5%. This is due to the more nodes which have been put into sleeping state compared with that of DT in every round.

4 Conclusions and Future Work

Minimizing energy consumption and prolonging the system lifetime has been a major design objective for wireless sensor networks. In this paper, we propose a node scheduling protocol, which prolong the system lifetime by turns off some redundant nodes for a period of time and waking up them in the future. This protocol can reduce the number of working nodes to the maximum extent without degrading the coverage and connectivity. Simulation shows that our protocol outperforms the peer with respect to the working node number and coverage percentage.

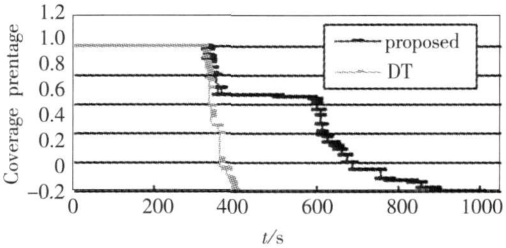


Fig. 4 Area dynamic coverage percentages versus time

For future work, we would like to look into the node scheduling issue without the geometric information because the energy cost and system complexity involved in obtaining the geometric information may comprise the effectiveness. Maybe some probability models, such as phase transition phenomenon[13], could be used to control the node density when the application doesn't require a complete coverage so stringently.

References

[1] Govindan E D, Heidemann R, Kumar J S. Next century challenges: Scalable coordination in sensor networks. Proceedings of the ACM MobiCom 99. New York: ACM Press, 1999. 263−270.

[2] Akyildiz I F, Su W L, Sankarasubramaniam Y, *et al*. A survey on sensor networks. IEEE Communications Magazine, 2002, 40(8): 102−114.

[3] Mainwaring A, Polastre J, Szewczyk R, *et al*. Wireless sensor networks for habitat monitoring. ACM International Workshop on Wireless Sensor Networks and Applications. New York: ACM Press, 2002, 88−97.

[4] Zhang Honghai, Hou J C. Maintaining sensing coverage and connectivity in large sensor networks. Wireless AdHoc and Sensor Networks, 2005, 1(1): 89−123.

[5] Wang X, Xing G, Zhang Y, *et al*. Integrated coverage and connectivity configuration in wireless sensor networks. ACM Conference on Embedded Networked Sensor Systems. New York: ACM Press, 2003. 28−39.

[6] Tian D, Georganas N D. A coverage-preserving node scheduling scheme for large wireless sensor networks. First ACM International Workshop on Wireless Sensor Networks and Applications. New York: ACM Press, 2002. 32−41.

[7] Ye F, Zhong G, Lu S, *et al*. Peas: A robust energy conserving protocol for long-lived sensor networks. Proceedings of the 23nd International Conference on Distributed Computing Systems. Washington DC: IEEE Computer Society, 2003. 28−37.

[8] Xu Y, Heidemann J, Estrin D. Geography-informed energy conservation for ad hoc routing. Proceedings of ACM MOBICOM'01. New York: ACM Press, 2001. 70−84.

[9] Santi P, Simon J. Silence is golden with high probability: Maintaning a connected backbone in wireless sensor networks. Proceedings of IEEE European Workshop on Wireless Sensor Networks. Washington DC: IEEE Computer Society, 2004. 106−121.

[10] Huang C F, Tseng Y C. The coverage problem in a wireless sensor network. ACM Int'l Workshop on Wireless Sensor Networks and Applications. New York: ACM Press, 2003. 115−121.

[11] Charkrabarty K, Iyengar S, Qi H, *et al*. Grid coverage for surveillance and target location in distributed sensor networks. IEEE Transaction on Computers, 2002, 51(12): 1448−1453.

[12] Meguerdichian S, Koushanfar F, Qu G, *et al*. Exposure in wireless ad-hoc sensor networks. Proceedings of the International Conference on Mobile Computing and Networking. New York: ACM Press, 2001. 139−150.

[13] Krishnamachari B, Wicker S B, Béjar R. Phase transition phenomena in wireless ad-hoc networks. Proceedings of the Symposium on Ad-Hoc Wireless Networks. Washington DC: IEEE Computer Society, 2001. 2921−2925.