Energy-Efficient Location-Independent *k*-connected Scheme in Wireless Sensor Networks[*]

Xiaofeng Liu[1], Liusheng Huang[1], Wenbo Shi[1], Hongli Xu[1]

[1](Department of Computer Science and Technology, University of Science and Technology of China, Hefei 230027, China)
{xfliu, shiwenbo}@mail.ustc.edu.cn, {lshuang, xuhongli}@ustc.edu.cn

Abstract. The reliability of communication can be enhanced by increasing the network connectivity. Topology control and node sleep scheduling are used to reduce the energy consumption. This paper considers the problem of maintaining *k*-connectivity of WSN at minimum energy level while keeping only a subset of sensor nodes active to save energy. In our proposed scheme, each node is assumed to have multiple power levels and neighbor proximity not exact location information is adopted. Firstly the network partition is attained by power based clustering, and next nodes are divided into equivalent classes according to the role of data forwarding to different adjacent clusters. Then Node Scheduling and Power Adjustment (NSPA) algorithm selects a subset of nodes with different power levels to construct the local minimum energy graph while maintaining network connectivity. If the number of intra-cluster nodes which have adjacent clusters exceeds a certain threshold, *k*-NSPA is employed. Finally, a *k*-connected topology can be obtained. The simulation shows that our scheme can obtain the redundant nodes while maintaining network *k*-connected and it is more energy efficient compared with previous work.

Keywords: *k*-connectivity, power, clustering, equivalence

1 Introduction

Wireless sensor networks (WSNs) are being increasingly deployed in severe areas to monitor the environment [1, 2]. In these applications, the network must be maintained connected to ensure the availability and reliability of communication. WSNs systems always contain a large number of nodes, due to the distributed area is large and the environment around is complicated, changing the batteries to renew the node energy is not practical. So sensors are required to be redundantly deployed to accommodate unexpected failures and extend the network lifetime. If idle sensors are not asleep, then redundant node deployment does not necessarily improve the connected coverage time of the field. So an important challenge of WSNs is how to maintain network communication connectivity and utilize the redundant nodes to extend the

---

[*] Supported by the National Grand Fundamental Research 973 Programs of China under Grant No.2006CB303006, No.2007CB316505 and the Knowledge Innovation Project of the Chinese Academy of Sciences.

network lifetime. An important frequently addressed objective is to determine a minimal number of working sensors required to maintain the connectivity. Therefore, the network topology should be controlled by selecting a subset of nodes to actively monitor the field and putting the rest nodes into sleep. The existing researches on node scheduling [10-15] are mainly address the scheduling mechanism to maintain the connectivity under maximal power. There are many researches [3-9] on topology control to gain energy efficiency. We can combine node scheduling and topology control to realize energy efficiency while maintaining connectivity. Most proposed protocols for topology control and node scheduling assume that nodes can estimate their locations or at least the directions of their neighbors (e.g., [14, 15]). In this work, we focus on applications in which location is unnecessary and possibly infeasible. Thus, we need redundancy nodes check that are based on neighbor proximity rather than on locations. Location independent connected coverage problem researches [16, 17] aimed at the relationship of neighbor set associated the node to achieve connected coverage. They are mainly based on the maximal power without energy efficient topology control, so they may not reach the energy efficient objective. Therefore, it is an appealing idea to make use of the neighbor proximity together with power topology control to provide network connectivity.

The contribution of our work is introducing an energy efficient location-independent *k*-connected scheme by multi-level power topology control and node scheduling relying on node equivalence relationship. It saves energy by turning off the forwarding units of nodes which are redundant for the desired connectivity by multi-level power control. The benefits of the proposed technique are twofold. First, the node clustering technology is adopted to get one hop connected clusters and its adjacent clusters; by the equivalent role they act in data forwarding to the adjacent clusters, the intra-cluster nodes are divided into some equivalent classes and the redundant nodes are found while maintaining required connectivity. Second, the energy efficient topology is constructed while maintaining *k*-connectivity by multi-level power control without knowing node locations.

The rest of this paper is organized as follows. Section 2 gives an overview of related work. In Section 3, the proposed clustering scheme and energy efficient *k*-connected scheme are presented. Section 4 discusses the performance evaluation of the proposed scheme. Concluding remarks of our research are made in Section 5.

2 Related Work

Power control is quite a complicated problem. Kirousis simplifies it as a range assignment (RA) problem [3]. The objective of RA is to minimize the network sending power (minimize the total power of all the nodes) while maintaining network connected. RA problem could be solved in $O(n^4)$ polynomial time in one dimension, but in two dimensions [4] and three dimensions [3], it is NP hard. Thus trying to finding the best result of the power control is not practical, but the feasible result can be given in special application level. The existing work is mainly based on reducing the sending power to prolong the network life.

In COMPOW [5], all the sensor nodes adopt the same sending power to minimize the network power while keeping connectivity. When the nodes are distributed uniformly, this algorithm shows good performance. But isolated nodes will lead to larger sending power for all the nodes. LUSTERPOW [6] improves that. It uses the minimal power not the common power to forward to next hop. CBTC [7] is based on direction while keeping connectivity. This kinds of algorithms based on direction require reliable direction information, thus need to be equipped with several antennae and high capability. DRNG and DLMST [8] are typical algorithms based on adjacent graph. The power control based on adjacent graph requires accurate location information. XTC [9] algorithm uses the receiving power intensity instead of the distance metric in RNG. It does not require the location information, but not practical in some extent.

The sensor nodes coming into sleep status can save energy consumption. Kumar presents a simple sleep scheduling algorithm RIS [10], in which the node independently decides itself to go to sleep or not in some probability at the beginning of every period. Obviously, RIS requires strict time synchronization. MSNL [11] proposed by Berman views the node sleep scheduling problem as a maximal the network lifetime problem with coverage restricted. It also needs accurate location information and there may be many nodes coming into sleep at the same time. LDAS [12] without requiring location information presented by Wu is based on the fractional redundancy to schedule the nodes, offering the coverage statistical guarantee. HEED [13] is a typical Level based node scheduling algorithm, which realizes clustering by periodic iteration according to the residual energy and communication cost of intra-cluster. HEED adopts average minimum reach power (AMRP) as the communication cost when selecting cluster head, which offers a uniform clustering mechanism not like other clustering schemes. HEED realizes clustering independent of the network size and it integrates the lifetime, extendibility and load-balance into consideration ignoring the node distribution. It is executed independent of synchronization, but no synchronization leads to bad clustering quality.

3 Network Partition and *k*-Connected Scheme

We first introduce our system assumptions and then describe the proposed scheme for determining node redundancy. At last we construct *k*-connected energy efficient topology.

3.1 System Model

The assumptions are listed as follows:

1) Nodes are randomly and redundantly deployed. They have similar batteries and energy consumption rates. And they have multi-level power which can be used to obtain the neighbor proximity achieved by checking whether the receiving power is in some bound or not, which means that the neighbor nodes will be sorted into multi-level sets according to the power levels. The minimal power level is the required sending power for communication.

2) Nodes have omni-directional antennae and do not possess localization capability. Thus, node locations and relative directions of neighbors cannot be estimated. We adopt the antenna model as follows: Assume sensors transmit with a power P_s, let the signal attenuation over space be proportional to some exponent γ of the distance d between two nodes, times the antenna directivity gain G, ($G = 1$ for omni-directional antennae), that is, $P_r / P_s = lG^2 d^{-\gamma}$, with $2 \le \gamma \le 5$, where *c* denotes a proportionality constant, and P_r denotes the minimum required receiving power for communication.

Given connected graph *G*, try to construct a connected energy minimum graph *H*. For each node *u*, it will be assigned transmission power level, and our objective is to minimize transmission power while maintaining the network connectivity. Therefore, we need to construct *H* with as few nodes as possible to consume as low power as possible. We offer a distributed approximate algorithm to address this objective.

3.2 Network Partition and Equivalence Classification

In this subsection, we will introduce a distributed network clustering scheme to provide one hop connected clusters and the sorting of the multi-level neighbor nodes into several equivalent classes. The basic idea of clustering works as follows: First, virtual cluster head method is adopted. When neighbors initiate a link with the cluster, the reply will be answered by the virtual head. In the initiative stage, a few of nodes (called virtual cluster heads) spontaneously broadcast inviting messages to its neighbors at the lowest power level. Any neighbor node decides whether or not to join the cluster dominated set by that sponsor according to the receiving power. Then this set will send messages to its neighbors following a sequence of power levels in an ascending order. In this way, the set is enlarged bigger and bigger until each node has an ascription at last, then the clustering is finished.

This strategy contains 3 kinds of messages: 1) “Hello” message which is used in initiating a cluster; 2) “Probe” message that is to ask for an ascription; 3) “Reply” message used for notifying others about its own response.

A. Multi-level Power Control Based Clustering and Adjacent Clusters Identification

1）Initially, some sponsors start to establish the clusters. Each of them appoints itself as the virtual head and makes an identification of this cluster.

At first, the virtual head broadcasts “Hello” message at the lowest power level P_0, see the Table 1 (Formalization and Description). Referred to the typical antenna model as mentioned in section 3.1, the receiving power can be described as a function of sending power and distance, which is formulized as $P_r = f(P_s, x)$. Each neighbor whose receiving power is in $[f(P_0, R_0/2), f(P_0, 0))$ will join into the cluster of this sponsor and CDS_0 is obtained. Then all nodes in CDS_0 will broadcast “Hello” message at sending power level P_1 (as shown in Fig.1). When the power level of all nodes in the cluster is increased from $P_{i\text{-}1}$ to P_i, the range of new cluster will cover the range of original one and they follow an equation as $R_{i-1} + 2x_i = R_i$, so $x_i = (R_i - R_{i-1})/2$. By the formula $P_r = f(P_s, x)$, node whose receiving power is in $[f(p_i, x_i + R_{i-1}),\ f(P_i, R_{i-1})]$

declares to join in this cluster and set the ascription cluster ID. Then CDS_{i-1} is updated to CDS_i .

Table 1. Formalization and Description

NOTATION	Descriptions
m	Total number of levels adjustable for power
P_i , R_i $(i = 0,1,\cdots,m-1)$	Sending power and Maximal communication range at P_i
CDS_i $(i = 0,1,\cdots,m-1)$	Cluster dominating set at P_i
CDS_{ij} $(i = 0,1,\cdots,m-2,$ $j = i+1,\cdots,m-1)$	Maximal communication coverage set of CDS_i
x_i $(i = 0,1,\cdots,m-1)$	Outspread range of CDS_i at power P_i
CDS , $CDS_{\max}$	Final cluster dominated set and coverage set
C_i $(i = 1,\cdots,k)$	Adjacent cluster i
G_i $(i = 1,\cdots,k+1)$	Equivalent nodes set of a cluster

All nodes in CDS_i send messages to the neighbors at power level P_j , $i < j < m$, then $CDS_{i\,j}$ is established. That is to say, $CDS_{i\,j} - CDS_i$ contains the nodes which are in the communication coverage of CDS_i at P_j but not belong to CDS_i . $CDS_{i\,j} - CDS_i$ means the neighbor set of CDS_i based on power P_j control. Assume final cluster dominated set and coverage set as CDS and $CDS_{\max}$. CDS relays messages via nodes in $CDS_{\max} - CDS$, so $CDS_{\max} - CDS$ consists of nodes those relay packets to the adjacent clusters. Each node in $CDS_{\max} - CDS$ will save this cluster ID as one of its adjacent clusters.

2) Each node checks up its cluster ID. If it finds that it does not belong to any cluster, it will broadcast the "Probe" message at the max power level P_{max} . After a certain period, if no "Reply" message is received, it will choose a random number as its cluster ID and return to 1).
3) When a node receives a "Probe" message, it will judge itself whether a virtual cluster head. If it is and its receiving power is in $[f(p_i, x_i + R_{i-1})P_m / P_i,\ f(P_i, R_{i-1}) P_m / P_i]$, then it will respond to the sender. Otherwise, the "Probe" message will be discarded.

During the process of clustering, if some clusters have nodes in common, the cluster which has the most nodes will continue, while others have to withdraw. So nodes in the common area are notified their cluster ID as the same as the biggest cluster. Nodes in smaller clusters not belonging to intersection set cluster ID as Null.

B. Equivalence Classification

After clustering, according to the forwarding communication function to different adjacent clusters, nodes are divided into many equivalent groups (as shown in Fig. 2). Assume there are n nodes in cluster A, and cluster A has ω adjacent clusters, noted as adjacent cluster C_j , $1 \le j \le \omega$. Intra-cluster nodes are divided into $\omega + 1$ groups like

$\{G_1, G_2, \cdots, G_\omega, G_{\omega+1}\}$. Nodes in the same group are equivalent according to forwarding role, noted as *equivalent property*. If node *u* in cluster *A* is in the coverage of adjacent cluster C_j at the power level of C_j, $1 \le j \le \omega$, i.e. $u \in CDS_{\max}(j) - CDS(j)$, then $u \in G_j$, all the nodes in G_j are equivalent as a role to relay packets to cluster C_j. If node *u* in cluster *A* is not in the range of any adjacent cluster, i.e. $u \notin CDS_{\max}(j) - CDS(j)$, $\forall j \in \{1, 2, \cdots, \omega\}$, then $u \in G_{\omega+1}$, that is to say, node *u* will not be chosen as a relay node by any adjacent cluster. The nodes for relaying are all in $G_1, G_2, \cdots, G_\omega$.

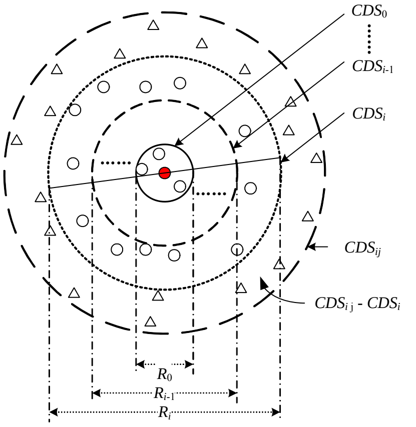
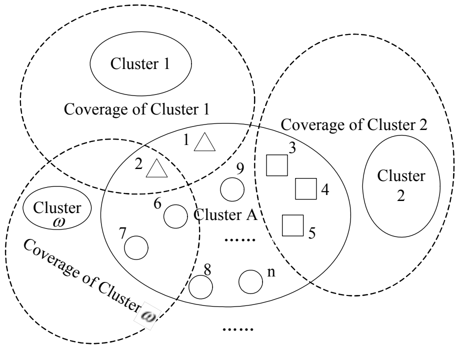


Fig.1. Some correlative sets in clustering.



Suppose cluster A has nodes 1, node 2, ······ and node n and has adjacent clusters: cluster 1, cluster 2, ······ , and cluster ω.

i) In cluster A, node 1 and node 2 are equivalent to cluster 1.

ii) In cluster A, node 3, node 4 and node 5 are equivalent to cluster 2.

······

Node 9 and node ··· are not in the coverage of any adjacent cluster.

Fig. 2. The equivalent classes after node clustering

3.3 Node Scheduling

From the process of clustering, we can find that any node in the network will be classified into a cluster, and any two clusters do not have a node in common. Considering the process of cluster establishment, we can obtain that the intra-cluster nodes are one hop connected by using a method of induction. The new cluster dominating set is extended by extending transmission range to R_i. Therefore they will be in each other's range at P_i. Now we consider some problems as follows:

A. The Node Redundancy Problem

Any node in intra-cluster, suppose $u \in G_i$, $1 \le i \le \omega$, they are equivalent to relay messages to their adjacent cluster C_j and in the transmission range of each other. If $|G_i| > 1$, it shows that there are redundant nodes in G_i, so just turn off the redundant nodes and wake up them by node sleeping schedule later. Look at such an occasion where node *u* belongs to a few of equivalent groups, for example, $u \in G_i \cap G_j \cap \cdots \cap G_k$. If *u* is turned on, all nodes like $v \in G_i \cup G_j \cup \cdots \cup G_k - u$ will be considered as redundant nodes, so turn them off. Denote adjacent clusters number of node *u* as index(*u*), i.e.

equivalent properties. What is optimal for energy saving is to turn on the low power level nodes those have the most equivalent properties.

B. The Problem of Connectivity between Adjacent Clusters

If a node *u* in cluster *A* is selected to be turned on, moreover $u \in G_i$, suppose *u* in the transmission range of adjacent cluster C_i at power level P_j, there will exist a node *v*, $v \in C_i$, such that node *u* and *v* are connected with each other at sending power level P_j. If node v in adjacent cluster is turned on, nodes which are in the same equivalent group as *v* will be regarded as redundant nodes.

C. The Problem of Power Asymmetry between Adjacent Clusters

After node clustering, if two adjacent clusters *A* and *B* are in different sending power levels P_A and P_B, and there exist two nodes $u \in A$, $v \in B$, such that *u* and *v* can hear each other at power level P_A or power level P_B, then choose the bigger bound $\mathbf{max}\{P_A, P_B\}$ to guarantee that intra-cluster nodes can connect with each other.

Node Scheduling and Power Adjustment Algorithm (NSPA)
Input: A set of sensor nodes with different power levels which are obtained by the network partition scheme and some clustering information, in which adjacent index denotes the equivalent properties of the node.
Output: A connected energy-efficient graph *H*.

```
NSPA Process //running by active nodes
    while (there are clusters without running this process)
        Sort the nodes according to adjacent index descending, noted as link L.
        Put the adjacent clusters' ID in the set S.
// find minimum nodes set connected with adjacent clusters
S1:     for the node u in the descending link L
            if (u.adjacent_cluster_ID element not in S)
                Delete the node from the link L and turn off u
            else
                Delete element in u.adjacent_cluster_ID from S
            $L = L \rightarrow next$
        if ( S is Null)   break;
        for each node v in the link L
            Delete the node from the link L and turn off the node v
// search the nodes in adjacent clusters connected with L
        for each node u in the link $L \rightarrow head$
            for each cluster c in u.adjacent_cluster_ID
                Search v in c connected with u with the maximal adjacent index
                Set max{u.power-level, v.power-level} for u and v
                Sort the nodes except v by adjacent index in c descending, link C.
                Put adjacent clusters' ID of c except the current cluster in the set S.
                Delete element in v.adjacent_cluster_ID from S
                View the cluster c as the current cluster and C as L, goto S1
  Return the active node set
```

Theorem 1: Given a redundantly connected graph G, topology H is connected after NSPA algorithm.

Proof: The final topology of the network consists of many clusters and each cluster has its own adjacent clusters. If there exists one cluster does not have any adjacent cluster, then the original network is not connected. Suppose two adjacent clusters *A* and *B*, there exists a node *u*, $u \in CDS(B)$, and $u \in CDS_{\max}(A) - CDS(A)$. Node *u* in cluster *B* is a forward node for cluster *A*. If no such a node *u* exists, it shows that there is a cluster not in the transmission range of the other, so they are not adjacent clusters. Any cluster will connect to CDS through relay nodes in $CDS_{\max} - CDS$. Because any two adjacent clusters are connected, the network topology cluster based is connected. Furthermore, those intra-cluster nodes can hear each other within one hop, so they are connected. By NSPA which turns off some redundant nodes, the cluster is in the communication coverage of any intra-cluster node and keeps the ability to relay messages to its adjacent clusters. Connectivity exists between any two of the clusters, so after node scheduling, the topology of network *H* is also connected. □

3.4 *k*-connected Algorithm

During clustering, we add an exit condition into the clustering process that the number of nodes which has adjacent clusters in this cluster is no less than *k*. And we try to find the minimum power consumption for active nodes set while keeping the graph *k*-connected. After running Alg. NSPA, the localized active set is obtained. Suppose the set of intra-cluster nodes awake is *X*, if $|X| \geq k$, the connectivity requirement is satisfied as proved in theorem 2, otherwise, in the cluster, choose at least $k - |X|$ redundant nodes which have adjacent clusters and turn them on to meet the requirement of *k*-connectivity. Let *Z* denote the node set which is turned on. Assume *E* represents the nodes set which is turned on in adjacent clusters connected with *Z*, satisfying $|E| \geq k - |X|$. In order to reduce energy as much as possible, we wake up the nodes in adjacent clusters whose power is no more than the redundant nodes in current cluster. Meanwhile, wake up the nodes which are connected with them in adjacent clusters.

_k_-connected Node Scheduling and Power Adjustment Algorithm (_k_-NSPA)
Input: The output of NSPA and the redundant nodes set of every cluster
Output: A *k*-connected energy-efficient graph *H*.

_k_-NSPA Process

```
while (there are clusters without running this process)
    if ($|X| \geq k$)    return $X$
    Sort redundant nodes by the adjacent cluster power level ascending, link $L$.
    for node $u$ in the descending link $L$
        $z = z + 1$ // initializing $z = 0$
        Turn on $u$ and the appropriate nodes in $E$
        if ( $z \geq k - |X|$ and $|E| \geq k - |X|$)    break;
        $L = L \rightarrow next$
Return the active nodes set
```

Theorem 2: After *k*-NSPA process, the network H is *k*-connected.

Proof: Given a connected graph *G*, after the classification of equivalent groups, $\forall u \in G$ can hear any intra-cluster node within one hop. The number of intra-cluster nodes which have adjacent clusters is no less than *k*, so the number of intra-cluster nodes is no less than *k*. After running *k*-NSPA algorithm, the graph *H* obtained is a topology with some clusters. Any set with a number of $k-1$ nodes in the graph, $K = \{u_i \mid u_i \in H, 1 \le i \le k-1\}$, test the connectivity of $H-K$. In cluster *A*, assume *X* represents the active nodes set after Alg. NSPA, *Z* denotes redundant nodes set which will be turned on after Alg. *k*-NSPA. Suppose there are *n* nodes from *K* in cluster *A*, $n \le k-1$, it is obvious that $|X+Z-K| \ge 1$. If $n = k-1$, $\forall u \in X+Z-K$, if $u \in X$, then there exist some nodes in adjacent clusters which are connected to u; if $u \in Z$, while *E* represents the redundant nodes set which are turned on in adjacent clusters connected to *Z*, $|E| \ge k - |X|$, then there exist some nodes in adjacent clusters which are connected to *u*. If $n < k-1$, there exist nodes removed from other clusters, if these nodes are not in the adjacent clusters of the current cluster, the connectivity will not be affected, assume these nodes are in the adjacent clusters, if $n = k-2$, then $|X+Z-K| \ge 2$, it means removing a node from the adjacent cluster, because of $|E| \ge k - |X|$, i.e. $|E| + |X| \ge k$, this node is connected with at most one node in $X+Z-K$, therefore, there must exist a node in $X+Z-K$ connected with adjacent clusters; when $n < k-2$, the same as above.

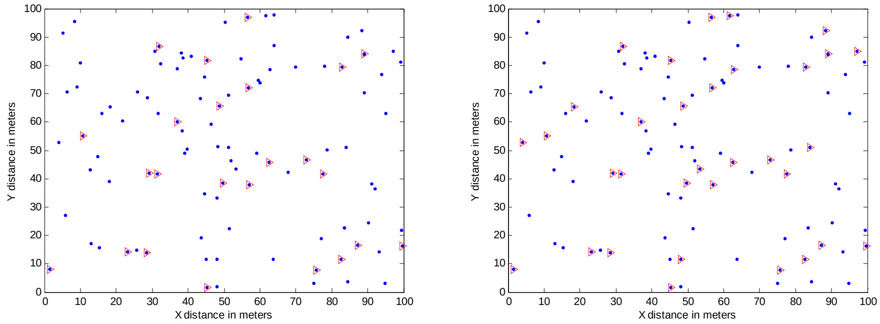
Above all, $H-K$ is still connected, so network *H* is *k*-connected. □

4 Performance Analysis and Simulation

We evaluate the energy-efficient scheme through simulation. Assume that *n* nodes are randomly and redundantly distributed in 100 × 100 square meters field. We focus on a snapshot during network operation where the energy of each node can be scaled in multi-level power. We assign the maximal power level of the nodes such that the transmission range of the nodes is all 30 meters and there are 6 power levels with different transmission ranges. Nodes have omni-directional antennae and do not possess localization capability, adopting the antenna mode described in section 3.1. Then we focus on the following metrics: (1) size of the active set for maintaining connectivity, (2) size of the active set for maintaining *k*-connectivity, and (3) energy consumption in each case. For simplicity, we do not simulate the energy costs associated with control messages during the equivalent nodes network partition.

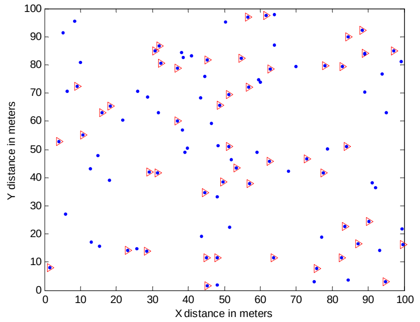
3.1 Connectivity and Active Set

We choose $n = 100$, denote the active set as *VA*, after running the NSPA algorithm, there is only 24 nodes being active to maintain connectivity with different power levels, all the nodes in the communication range of *VA*. In this topology, we run the *k*-NSPA algorithm to obtain the *k*-connected minimum energy graph with different sizes of active sets as shown in Fig.3. From the result we can obtain that only a subset of



(a) NSPA, $|VA| = 24$ (b) 3-NSPA, $|VA| = 33$

Fig. 3. The active nodes set under *k*-NSPA algorithm with different *k* values.



(c) 5-NSPA, $|VA| = 49$

Fig. 3. (c)

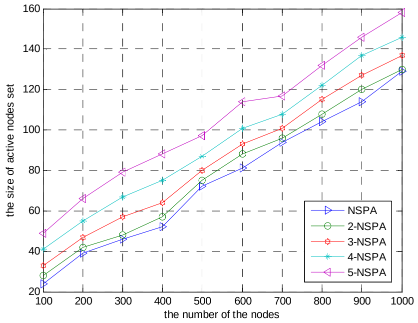


Fig. 4. The active set under *k*-NSPA algorithm in different topology

the whole nodes are awake for forwarding, and $|VA|$ increases along with value k which refers to the network connectivity. This scheme is different from the previous research on topology control schemes which adjust the power of each node and the node scheduling scheme in which the node controls the status of itself to be active or sleep by judging the information of itself or being controlled by the cluster head. After NSPA algorithm, we select a minimum nodes in multi-power levels to get the local minimum energy graph while maintain network connected. Increasing the network connectivity, high communication reliability can be enhanced. After *k*-NSPA, a *k*-connected topology may be obtained.

In Fig.4, we give the active set size of the cases with different node number n and the different value k . Each point in our results is the average of 10 experiments of different random topologies. The algorithm offers a method of how to gain a *k*-connected graph from a connected graph by adding the condition the number of the nodes intra-cluster having adjacent cluster more than k . And awake the sleep nodes to enhance the network connectivity. This is a requisite condition to obtain the *k*-connected graph.

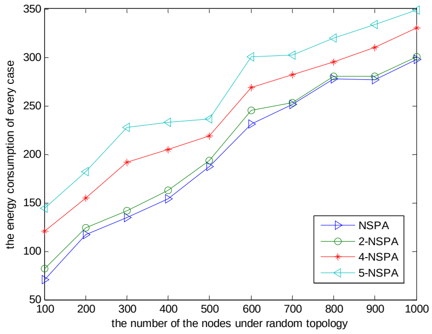


Fig. 5. Energy consumption of NSPA and *k*-NSPA in different topology.

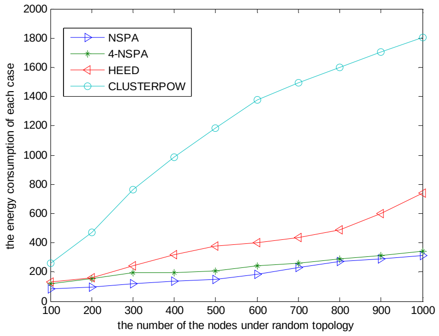


Fig. 6. Energy consumption of our scheme, HEED and CLUSTERPOW.

3.2 Energy consumption

After the network partition and node scheduling, we can obtain the topology *H*. In our simulation, we assume the power level of the node as the proportion of energy consumption. The energy consumption is the total power levels of all the nodes. In the power level adjustment, select the nodes in these equivalent classes which can minimal the energy consumption locally. This algorithm is localized and distributed. We can obtain the localized minimum energy consumption, therefore achieving the approximate minimum energy graph which maintains the required network connectivity. The energy consumption increases as the network size and the network connectivity increase as shown in Fig.5. There is no node scheduling in COMPOW and LUSTERPOW. If the network is redundantly deployed, all the nodes keeping active leads to network disabled more early. So the energy consumption in these algorithms will be more than our scheme as shown in Fig.6. In the algorithm HEED, only node scheduling method is mentioned, there being no power control, in which all the nodes use the maximal power to send the packets. We compare the energy levels with ours, also shown in Fig.6. Obviously, our scheme is energy efficient.

5 Conclusion

This paper proposes a novel approach for topology control and node scheduling in the absence of location information. Our redundancy check relies on locally neighborhood proximity and equivalent classes by the association with the adjacent clusters. We incorporate our clustering scheme under multi-level power control and node scheduling into a distributed connected algorithm (NSPA). Next we add an exit condition in clustering, and then *k*-NSPA is employed, a *k*-connected topology may be obtained. Our scheme incurs low energy consumption and can significantly reduce the set of active nodes. Simulations show that the achieved energy efficiency by our scheme is significant to those achieved by some typical protocols. Although in the initial stages, such a location-independent *k*-connected scheme can be beneficial and effective for sensor applications that require high reliability and long lifetime of a specified sensor field.

References

1. T. He, S. Krishnamurthy, J.A. Stankovic, T.F. Abdelzaher, L. Luo, R. Stoleru, T. Yan, L. Gu, J. Hui, and B. Krogh. Energy-Efficient Surveillance System Using Wireless Sensor Networks. In: ACM MobiSys, June 2004, pages 270--283.
2. R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler. An analysis of a large scale habitat monitoring application. In: Proc. 2nd ACM Conference on Embedded Networked Sensor Systems (SenSys ’04), Nov. 2004, pages 214--226.
3. Kirousis LM, Kranakis E, Krizanc D, Pelc A. Power consumption in packet radio networks. Theoretical Computer Science, 2000, 243(1-2):289−305.
4. Clementi A, Penna P, Silvestri R. On the power assignment problem in radio networks. ACM/Kluwer Mobile Networks and Applications (MONET), 2004,9(2):125−140.
5. Narayanaswamy S, Kawadia V, Sreenivas RS, Kumar PR. Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol. In: Proc. of the European Wireless Conf. Florence, 2002. 156−162.
6. Kawadia V, Kumar PR. Power control and clustering in ad-hoc networks. In: Mitchell K, ed. Proc. of the IEEE Conf. on Computer Communications (INFOCOM). New York: IEEE Press, 2003. 459−469.
7. Li L, Halpern JY, Bahl P, Wang YM, Wattenhofer R. A cone-based distributed topology control algorithm for wireless multi-hop networks. IEEE/ACM Trans. on Networking, 2005,13(1):147−159.
8. Bahramgiri M, Hajiaghayi MT, Mirrokni VS. Fault-Tolerant and 3-dimensional distributed topology control algorithms in wireless multihop networks. In: Proc. of the IEEE Int’l Conf. on Computer Communications and Networks (ICCCN). 2002. 392−397.
9. Wattenhofer R, Zollinger A. XTC: A practical topology control algorithm for ad-hoc networks. In: Panda DK, Duato J, Stunkel C, eds. Proc. of the Int’l Parallel and Distributed Processing Symp. (IPDPS). New Mexico: IEEE Press, 2004. 216−223.
10. Kumar S, Lai TH, Balogh J. On k-coverage in a mostly sleeping sensor network. In: Haas ZJ, ed. Proc. of the ACM Int’l Conf. on Mobile Computing and Networking (MobiCom). New York: ACM Press, 2004. 144−158.
11. Berman P, Calinescu G, Shah C, Zelikovsky A. Efficient energy management in sensor networks. In: Xiao Y, Pan Y, eds. Proc. of the Ad Hoc and Sensor Networks, Series on Wireless Networks and Mobile Computing. New York: Nova Science Publishers, 2005.
12. Wu K, Gao Y, Li F, Xiao Y. Lightweight deployment-aware scheduling for wireless sensor networks. ACM/Kluwer Mobile Networks and Applications (MONET), 2005,10(6):837−852.
13. Younis O, fahmy S. HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. IEEE Trans. on Mobile Computing, 2004,3(4):660−669.
14. H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. Ad Hoc & Sensor Wireless Networks, 1:89–124, Jan. 2005.
15. X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. D. Gill, “Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks,” In: Proc. First ACM Conference on Embedded Networked Sensor Systems (SenSys’03), Nov 2003. New York.
16. Choudhury RR, Kravets R. Location-Independent coverage in wireless sensor networks. 2004. http://www.crhc.uiuc.edu/~croy/pubs
17. Ossama Younis. Marwan Krunz and Srinivasan Ramasubramanian. Coverage Without Location Information. IEEE International Conference on Network Protocols, ICNP 2007.