k^+ *Neigh*: An Energy Efficient Topology Control for Wireless Sensor Networks*

Dong-Min Son and Young-Bae Ko

Graduate School of Information and Communication,
Ajou University, Suwon, Republic of Korea
dongmin@uns.ajou.ac.kr, youngko@ajou.ac.kr

Abstract. For most applications in wireless sensor networks (WSNs), it is often assumed that the deployment of sensor nodes is unmanaged and random, so the density of local node may vary throughout the network. In high density areas, nodes consume more energy due to frequent packet collisions and retransmissions. One of the ways to alleviate this problem is to adjust the transmission power of each sensor node by means of efficient topology control mechanisms. In this paper, we propose an efficient topology control for energy conservation, named "k^+ *Neigh*." In our scheme, each sensor node reduces its transmission power so that it has minimum number of k neighbor nodes. Later, we will show that the preferred value of the k is 2 by simulation. In the performance evaluation, the proposed scheme can make significant energy saving with such a topology structure, while the network connectivity is guaranteed.

1 Introduction

Wireless sensor networks (WSNs) consist of a number of sensors that have responsibility for informing any sensed event to a centralized node (often, called a "sink") via multi-hop wireless transmissions. In general, sensor nodes are randomly deployed, so the local density of each node may vary according to their locations. In highly dense areas, sensor nodes may suffer from more contentions among themselves and a severe interference with their local neighbors. It is not difficult to expect that a high contention increases the possibility of packet collisions and hence retransmissions, resulting in faster energy depletion of sensor nodes. Moreover, it will increase the end-to-end latency of packet transmissions.

One of the solutions to alleviate this problem is to manage the network topology by adjusting a transmission power of each sensor node. An optimally adjusted transmission range of each node can decrease the frequency of packet collisions and improve the network performance with the effect of spatial reuse. However, it is not

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easy to get this optimal value because the connectivity from the whole network's point of view should be guaranteed, while keeping the transmission range of each node as small as possible. In this paper, we propose an efficient topology control algorithm for energy conservation, named "k^+ *Neigh*." In the proposed scheme, a sensor node tries to reduce its transmission power based on the value of k which represents the number of local neighbors of each node that can guarantee the network connectivity as well as energy efficiency. We argue that such a value of k can be utilized for the nodes to control their transmission power (i.e., to adjust its transmission range as optimal as possible). The transmission power control is possible in the real world sensor network. The Mica Mote, which is famous sensor node, can adjust its transmitting power in 255 different levels (e.g., from 0x01 to 0xff) [9]. Mica Mote has been developed at U.C. Berkeley and is now commercially available from Crossbow Inc. It is equipped with a low-power micro processor, 128K of program memory, 4 K of SRAM, and low power transceiver for wireless communication.

The rest of the paper is organized as follows. Related works on topology control schemes are presented in Section 2. Section 3 introduces our proposed scheme followed by simulation results in Section 4. We conclude our paper in Section 5.

2 Motivation and Related Work

Our k^+ *Neigh* protocol can be said to be motivated from the existing k-NEIGH topology control scheme [3]. The authors of [3] argue that some optimal form of topology can be created by having every node keep their number of neighbors below a specific value of k. The value k is chosen in such a way that the entire network is connected with high probability. The k-NEIGH topology control produces a symmetrically connected graph by addressing technical machinery of [4]. They show that setting k to 9 produces the optimal topology with high connectivity. They also argue this value of k can be minimized to 6 if applications accept weakly connected network topologies.

Now, we want to point out that these values of k (either 6 or 9) in the k-NEIGH protocol look too large to minimize energy consumption and interference among neighboring nodes in WSNs. In addition, we believe that k-NEIGH protocol can cause a severe problem of network partition in some cases. Therefore, we need to develop a better scheme for topology control both in terms of energy efficiency and network connectivity.

In order to guarantee complete network connectivity, each node should guarantee one more link towards the sink. To get the link, we use an Interest Message of the Directed Diffusion [5] with slight modification. The Interest Message has been proposed for data-centric paradigm. In WSNs, every sensing data is always reported to the monitoring terminal (e.g., sink). To make such procedure efficiently, sink names and diffuses its interest, each sensor node then collects and reports the named sensing data. The important feature is that the Interest Message is periodically diffused from the sink to the entire network. The Interest Message contains named task description such as data type, report interval, and task duration. Other than these task descriptions, we will add topology control information on the Interest Message.

One more thing that we consult from Directed Diffusion is data aggregation. The early model of Directed Diffusion provides in-network data aggregation as opportunistic aggregation at intermediate nodes along the established paths. However, the opportunistic path selection only provides chance of aggregation. Therefore greedy aggregation is proposed in [6]. In the greedy approach, path sharing mechanism improves early shared and merged path by using a greedy incremental cost. Similar to the greedy aggregation, we will also use a similar kind of information, named Cost-to-Sink (i.e., cost to reach the sink), to guarantee the path to sink.

3 Proposed Scheme: k^+ *Neigh Topology Control*

The ultimate goal of our work is to minimize energy consumption and radio interference while maintaining connectivity in wireless sensor networks. To accomplish this goal, we propose to adjust the number of neighbors per node into some optimal value. Such an approach can be thought to be similar to the existing k-NEIGH protocol in [3]. However, we propose a better solution here to resolve some limitations of the k-NEIGH which are already described in the previous section. Thus, we present a novel neighbor-based solution which guarantees the network connectivity with any value of *k* -- in section 4 we will show setting k to 2 is the optimal choice in terms of energy cost and spatial reuse. The proposed solution for energy efficient topology control is called as "k^+ *Neigh*", and consists of two phases: *Neighbor Discovery with MAC-level Beaconing*, and *Topology Control with Interest Message Exchange*. Note that the messages in both phases are periodically issued. The periodic *MAC-level Beaconing* allows to detect node failure, while the periodic *Interest Message* enables reconstruction of the topology without link failure. More details of each phase are described in the following subsections.

3.1 Neighbor Discovery Phase

In this phase, each sensor node discovers its neighbors by maintaining a neighbor table that is updated with periodic MAC-level Beaconing of Hello messages. Note that we assume sensor nodes have no or minimal mobility. Each node broadcasts its Hello message, which contains its identification (i.e., each node's ID information). The neighboring nodes obtain this message, and store the identification and the estimated distance to each of their neighbor table. The storing process is done in order of the distance. We assume that several techniques such as Received Signal Strength Intensity (RSSI) [7] or Time of Arrival (ToA) [8] can be used to estimate the distance between each sensor node. These techniques do leave room for criticism, but they can be effective in that they take lower cost than using the Global Position System (GPS). Although, in this paper, we present our scheme by using the distance information, the distance information can be substituted by other routing metrics such as signal strength or air-time cost. Therefore the problems when the distance information is utilized (e.g., multipath propagation, bit error rate) can be relieved by using these metric. For example, the signal strength reveals the radio interference (i.e., the radio interfered node is the actual neighbor node).

3.2 Topology Control Phase

After the end of the Neighbor Discovery phase, each sensor node will obtain a sorted neighbor table that contains the ID and the distance information of all of its physical neighbors. To reduce the medium access contention and the transmitting power of the nodes, each node *logically* adjusts the number of its local neighbors by selecting *k* smallest distanced entries from the original neighbor table. We call this logically selected list as *k-Neighbor List* (k-NL for short). The k-NL is included in the Interest Message that is initially issued by the sink, and it is later continuously modified and forwarded by the intermediate nodes. (We illustrate how an Interest Message looks like, and how it is used for topology control later in this subsection). Based on the information of k-NL, each node can verify which neighbors are symmetric to it. Here, a symmetric neighbor means that any two nodes are included in each other's k-NL that they can have a symmetric link between them. However the verification mechanism causes a problem. A node can have no symmetric neighbor because all of its neighbors may not include this node as their symmetric neighbor. In this case, that node is isolated from the network.

To resolve this problem, we devise the concept of special neighbor node for guaranteeing a link towards the sink. We call this special neighbor node as Node-to-Sink. Once a node sets another node as the Node-to-Sink, the node set as the Node-to-Sink should include that node even if it has more than k symmetric neighbors. To make an energy efficient topology, a node selects Node-to-Sink, which is the shortest distanced neighbor among which that is closer to the sink than the node. The distance from a node to its neighbors can be obtained by using the neighbor list, but the distance from a sink to the node cannot be known.

So we add one more information named Cost-to-Sink. The Cost-to-Sink is the accumulated value of the distance from the sink to the current node with the Interest Message. To get the appropriate accumulated value, the diffusion (message forwarding) sequence of the Interest Message is very important. Fundamentally, the procedure of our Interest Message diffusion is some what similar with the directed diffusion [5] in that the sending of the Interest Message starts from the sink. However, it is unique in that it does not use the random back-off forwarding that is used in the directed diffusion. Instead of the forwarding, we design "Distance-based Forwarding." Further description about this mechanism is given below:

Distance-based Forwarding. Assume that a generic node *u* sends a message to node *v*. To forward the message in ascending order of the estimated distance between node *v* and *u*, the receiving node v should send a message at time T_s within the sending interval T_{SI}. The time is obtained by using the first received message as the standard. The equation of T_s is as follows: (Distance between nodes u and v is denoted by d_{uv}, and Maximum transmission range of node is denoted by R_{MAX})

$$T_S = T_{SI} \times \frac{d_{uv}}{R_{MAX}} \quad (1)$$

Fig. 1 on the next page shows an example of our k^+ *neigh* topology control where *k* is set to 2. Fig. 1(a)-(e) shows the diffusion procedure of Interest Message. In Fig.

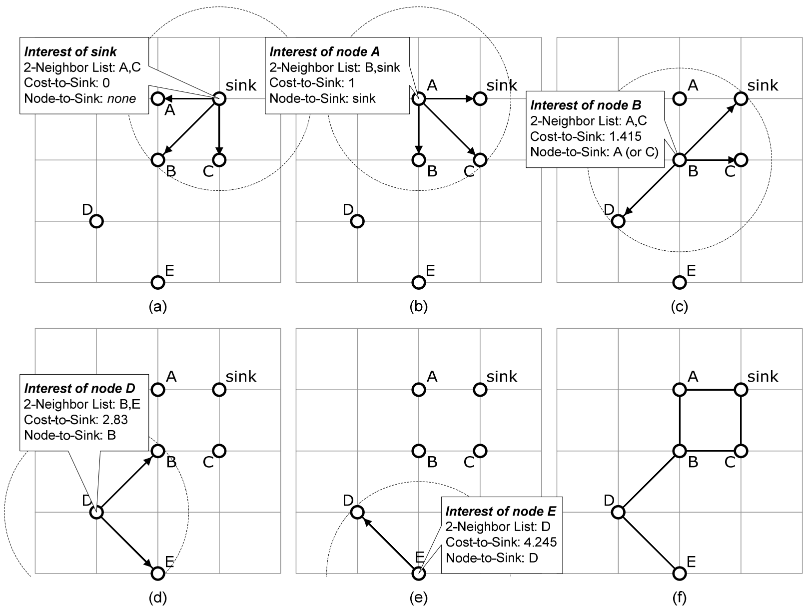


Fig. 1. Diffusion process of Interest Message for Topology Control. (a) Initially, sink generates an Interest Message with three types of information, i.e., 2-NL, Cost-to-Sink, and Node-to-Sink. (b) On receiving the Interest Message from the sink, node A modifies and rebroadcasts it. (Node C's transmission is omitted here) (c) After A's forwarding, node B forwards the message as it is farther than node A from the sink. (d) Node D also fills out the three info of Interest Message and forwards it. (e) Finally, node E does the same. (f) Final topology graph, where each node adjusts its power properly.

1(a), a sink initially transmits Interest Message with three types of information. To fill in the 2-Neighbor List, the sink picks out nodes A and C from its neighbor list. The Cost-to-Sink and Node-to-Sink attributes are set to 0 and none, respectively, as the node itself is the sink. When receiving this Interest Message from the sink, the neighboring nodes A, B, and C are required to update their Cost-to-Sink value. The Cost-to-Sink will be determined by a summation of the value included in the received Interest Message from the sink and the distance between the sink and the receiving node. That is, nodes A, B, and C will set their Cost-to-Sink values into 1, 1.415, and 1, respectively. After this setting, each node then decides when it should forward the modified Interest Message at the specific time, according to Distance-based Forwarding. If the sending interval (T_{SI}) is 1 second then node A and C forward the Interest Message at the time of 0.67 (= 1 × 1 / 1.5). In this case, although the sending time is same between node A and C, the actual sending time becomes different because the contention at MAC layer. Consequently, the Interest Message is diffused in the sequence of [sink, {A, C}, B, D, and E]. By this mechanism, every node can be assured to obtain the least Cost-to-Sink before forwarding.

Fig. 1(c) and (d) show the construction of the Symmetric Neighbor List (SNL) by exchanging of 2-Neighbor List attribute. In Fig. 1(d), node D includes nodes B and E into its 2-Neighbor List. However, in Fig. 1(c), node B did not include node D in its

2-Neighbor List, thus node D realizes that node B is not a symmetric neighbor. If node D cannot be a neighbor with node B then node D cannot connect to the sink. For this case, the Node-to-Sink attribute is utilized as illustrated in Fig. 1(d). Node D decides to set the Node-to-Sink to node B and includes node B in its Symmetric Neighbor List. Once node B gets the message that it has been set as the Node-to-Sink, then it has to include the node D to its Symmetric Neighbor List.

After the diffusion of the Interest Message, each node sets its transmission power to the power that is needed to transmit to the farthest node in SNL. Note that we assume the sensor nodes are able to control their transmitting power. Fig. 1(f) shows the resulting topology of our 2^+ Neigh Topology Control where k is set to 2. At initial time, the power of every node sets 1.5, so that the total energy cost is 9, but after topology control, the total energy cost becomes 7.245, thus we can save the energy amount of 1.755. This example is very simple and uniform. However, in practice, the topology can be untethered and unattended so the energy can be saved much more than this example. The further evaluation for energy cost in the random topology is shown in section 4.

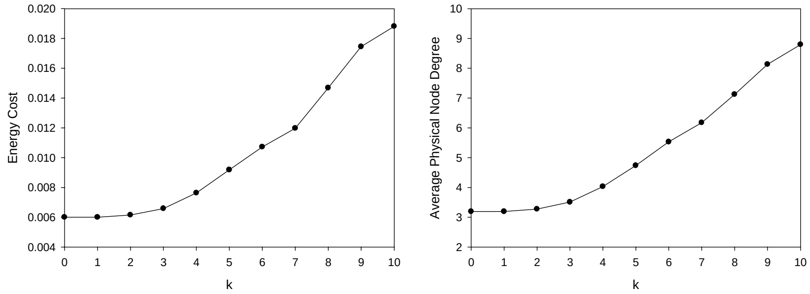
4 Performance Evaluation

In this section, we evaluate k^+ Neigh using NS-2 [10] simulator. The ultimate goal of simulation is to show that our proposed k^+ Neigh topology control protocol contributes to significant improvements of both energy efficiency and network capacity. For the purpose of a comparison, we consider the following two topology control algorithms:

- **Minimum Spanning Tree (MST):** Euclidian MST algorithm produces the topology which consumes minimum energy in data communication. Basically, MST can not be used easily in practical because it assumes that each node knows the global position of all other nodes in the network.
- **k-NEIGH**: As in the section 2, k-NEIGH algorithm insists that the number of physical neighbors of every node maintains equal to or slightly below a specific value k. We set the k to the value of 6, for small network (e.g., where the total number of nodes is under 100), and generally k is set by 9. We have considered the result of Phase 1 only (i.e., without pruning).

4.1 Simulation Environment

In our simulation, a total number of nodes *n*, ranges from 10 to 1000. To decide the network size, we consider the power control capability of Mica Mote series [9] and the empirical transmission range for ensuring connectivity (refer to [2] and [3]). In practice, the Mica Mote is able to adjust the transmission range by at most 150m. According to [2] and [3], when *n* is equal to 10 the transmission range should be empirically larger than $0.86622 \times r$, where *r* is a network radius. Thus we set the maximum transmission range to 86m when *r* is set to 100m. We use the two-ray ground model as a radio propagation model and an omni-directional antenna which



(a) (b)

Fig. 2. The performance results of k^+ Neigh for different values of the number of neighbors (a) Energy cost according to k. (b) Average physical node degree according to k.

having homogeneity gain in the simulation. We measure the following metrics: *energy cost*, and *physical node degree*.

We define the energy cost as the equation shown below:

$$c(PA) = \sum_{i \in N} (PA(i)) \quad (\mathbf{2})$$

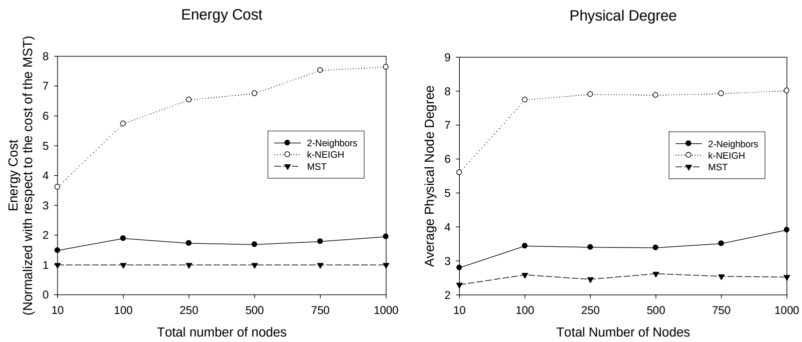
where PA is the power assignment which is adjusted at the end of the Topology Control Phase.

In our simulation study, we convert the distance to power according to the Friis free space model [11] and the two-ray ground reflection models [11] that are currently implemented in the well-known network simulator NS-2. The free space propagation model assumes the ideal condition, thus it is useful for short distance. On the other hand, the two-ray ground reflection model considers both the direct path and a ground reflection path. Therefore we consider the crossover point of two models (If the distance is less than 86.14m then the Friis model is applied otherwise the two-ray ground is used [10].)

The physical node degree represents the actual number of interfered neighbors. This notation can be distinguished from logical node degree because the logical degree shows only the number of one-hop symmetric neighbors. Therefore physical node degree is the more meaningful metric than the logical node degree in evaluating the actual contention at the MAC layer. In addition, the low physical node degree increases the spatial reuse, so that the network capacity becomes enhanced.

Before explaining more details of the simulation results, we have studied about the appropriate number of neighbors for energy efficient topology control by means of a simulation-based evaluation. The number of neighbors is denoted by k and indicates the intensity of the contention. Therefore the smallest value of k is recommended for topologies requiring the lowest contention. However if the number of neighbors becomes too few, it may cause instability of the network and cannot work on rigorous environments. Consequently, when adjusting the value of k, the energy cost and physical degree should be carefully considered.

To see the effect of the value k, we measure the energy cost and the physical degree by varying it from 0 to 10. 100 nodes are distributed randomly in the network.



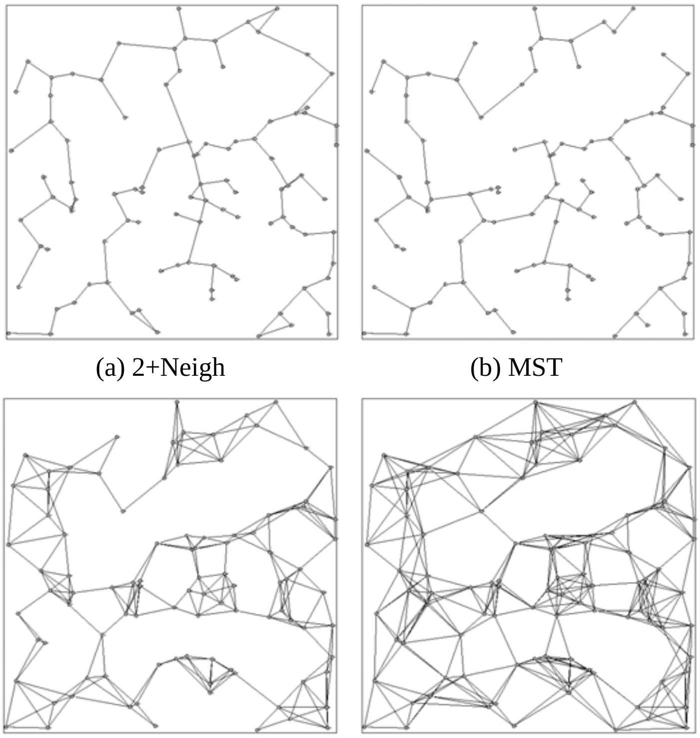
(a) (b)

Fig. 3. The performance results of 2-Neighbors compared with k-NEIGH and MST. (a) Energy cost according to the network size. The energy cost is normalized with respect to the cost of the MST. (b) Average physical degree according to the network size

In the first experiment, the result of energy cost is shown in Fig. 2(a). The interesting point is that the energy cost is almost the same when k=0 and 1. When k=0, each node can have no symmetric neighbor with an empty k-Neighbor List (i.e., 0-NL), so that a node purely relies on Node-to-Sink to create the symmetric neighbor. The symmetric neighbor from Node-to-Sink guarantees a path towards a sink. Likewise, it is difficult to make the symmetric neighbor for the 1^+ Neigh because it is rare to have each other as 1-NL of two nodes. So 1^+ Neigh also relies on Node-to-Sink and the result of 1^+ Neigh is similar with that of 0^+ Neigh. The 0^+ Neigh or 1^+ Neigh can be thought as good for extremely energy sensitive network environments. One more thing to observe is the energy cost of 2^+ Neigh is almost same as 0^+ Neigh. As previously stated, the large value of k makes the network stable. Therefore 2^+ Neigh is recommendable for energy efficient networks. Besides, the MST, which is considered as the optimal network topology scheme, tries to maintain its number of neighbors as two. This is made clearer by Fig. 2(b), which the physical degree values for k=0 and k=3 are shown to be similar. This means, when k is 2 or 3, a topology becomes energy efficient with a low contention while having more stable number of neighbors. Larger values over 4 may be suitable for applications requiring highly stable network environments, but at the cost of energy consumption.

4.2 Simulation Results

Performance results of 2^+ Neigh are reported in Fig. 3 compared with k-NEIGH, and MST. In Fig. 3(a), we show the energy cost which is normalized with respect to the cost of the MST. We can see the energy cost of 2^+ Neigh is significantly less than k-NEIGH and quite close to that of MST. This result is very meaningful because our scheme requires only 2n message where n is the number of nodes. Moreover the half of the required messages are relatively low cost MAC-level beaconing. We recall that the MST requires global position of every node so that n^2 messages should be exchanged. The average physical node degree of 2^+ Neigh topology control protocol is also reported in Fig. 3(b). The figure shows an evident result that the upper bound



(a) 2+Neigh (b) MST

(c) k-NEIGH (k=6) (d) k-NEIGH (k=9)

Fig. 4. Sample topologies produced by k+Neighbors, MST, and k-NEIGH Topology Control when n=100. We call the k+Neighbors where k=2 as "2+ Neigh." Note that *k* is set to 6 or 9 for the k-NEIGH in (c) and (d) above.

(k) of k-NEIGH is still large to reduce the number of physical neighbors. Our protocol achieves 30% lower average physical degree compared to k-NEIGH. For the proposed 2^+ Neigh protocol, we emphasize that the spatial reuse, which is represented by the physical node degree, is approximated to the sparsest possible topology (MST) while the cost of topology construction is tremendously reduced.

To compare the visual network topologies of k^+ Neigh, MST, and k-NEIGH, we use the graph drawing software called Himmeli [12]. The sample topologies generated by the various protocols for n=100 are shown in Fig. 4 on next page. In k^+ Neigh Topology Control, we set the value of k to 2, as recommend in section 4.1. Unlike our scheme, in k-NEIGH, the value of k is set to 6 and 9 as suggested in [3]. We recall that our scheme guarantees network connectivity even when k is set to 2. On the other hand, the k-NEIGH causes a severe problem of network partition if k is set to 2. Fig. 4 also shows that our 2^+ Neigh scheme significantly removes the number of over-connected links from k-NEIGH. Not only the topology of 2^+ Neigh looks similar to the MST (See Fig. 4(a) and (b), respectively), but 2^+ Neigh also has some more number of links for connection towards a sink (located in a center of all the figures). In result, our scheme is proved to be efficient in terms of energy cost and to be robust in terms of the available number of paths towards a sink.

5 Conclusion

Topology control has been proved to be an efficient method in improving both energy conservation and network capacity [1]. However, previous researches on topology control do not take into account the untethered and unattended sensor networks. For this reason, we proposed a novel topology control for sensor networks.

Our proposed scheme, named k^+ *Neigh*, tries to maintain *k* number of neighbors. This approach seems a bit like k-NEIGH [3] but the possible value of k is different. The k-NEIGH can not prevent network connectivity at a small k value. In contrast, the k^+ *Neigh* is connected by any value of the k. Among the values of the k, setting k to 2 is suggested for energy efficiency and network capacity. The k^+ *Neigh* defines two phases: Neighbor Discovery and Topology Control. In the Neighbor Discovery phase, each node sends Hello messages periodically and obtains the neighbor entries. In the Topology Control phase, the sink diffuses the Interest Message which contains information for creating the topology. Since the Interest Message is periodically sent, our k^+ Neigh topology network can recover and maintain network connectivity.

For further researches, we plan to study the sink mobility issues on the sparsest possible topology and the data aggregation method which can relieve traffic bottleneck. These investigations are expected to enhance k^+ *Neigh* Topology Control. We shall also implement our scheme on Mica Mote platform to show that this scheme is effective in the real sensor world.

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