A Topology Management Framework for Wireless Sensor Networks via Power Control

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Abstract—**The communication topology plays a key rule in the overall network performance. Topology management via power control has been addressed by many researchers to attain better utilization of available resources by reducing the complexity of the network topology. Energy conservation in these protocols is mainly achieved by utilizing lower transmission power levels. Like other types of wireless ad hoc networks, this feature makes their applicability in sensor networks equally attractive. However, most of the previous solutions were not designed while considering various data traffic patterns in wireless sensor networks (WSNs). We propose a topology management framework that dynamically adjusts transmission power levels to cater for several data traffic patterns. The simulation results show that the resultant fully-connected tree-like topologies offer an efficient tradeoff between available resources and the network topology complexity.**

Keywords-Topology Management; Power Control; Wireless Sensor Networks

I. INTRODUCTION

The design of wireless sensor network [1] architecture requires efficient tradeoff between available resources and network topology complexity. This tradeoff implies that the performance of the control protocols (such as route maintenance, shared medium access, scheduling etc) is strongly influenced by the complexity of underlying network topology. A topology management or topology control [2], [3], leads to a simpler communication graph where fewer links result in reduced energy consumption and efficient sharing of common resources such as a wireless channel.

The network topology can be managed in two ways. In the first approach [3],[4], a hierarchy of cluster-head nodes is obtained to construct a connected communication backbone of the network. The idea is to designate only a subset of nodes to carry out the network control functions and thus to reduce the communication overhead. The other approach is to employ a power control [2], [5], [6] mechanism where each node dynamically adjusts its transmission power to control the number of neighboring node. Since the physical degree of a node strongly influences the utilization of available bandwidth and energy consumption, selection of an optimal number of cluster-head/neighbors is the main objective of such algorithms. Due to the complexity and overhead involved with the topology management and dynamic power adjustment, existing protocols in both domains consider data traffic patterns as an afterthought.

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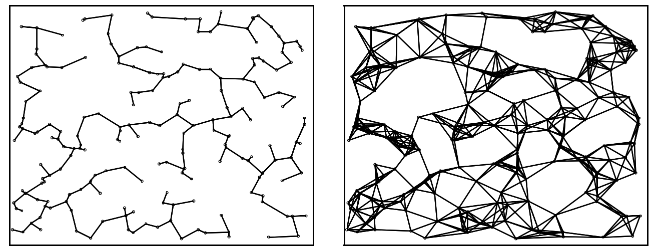


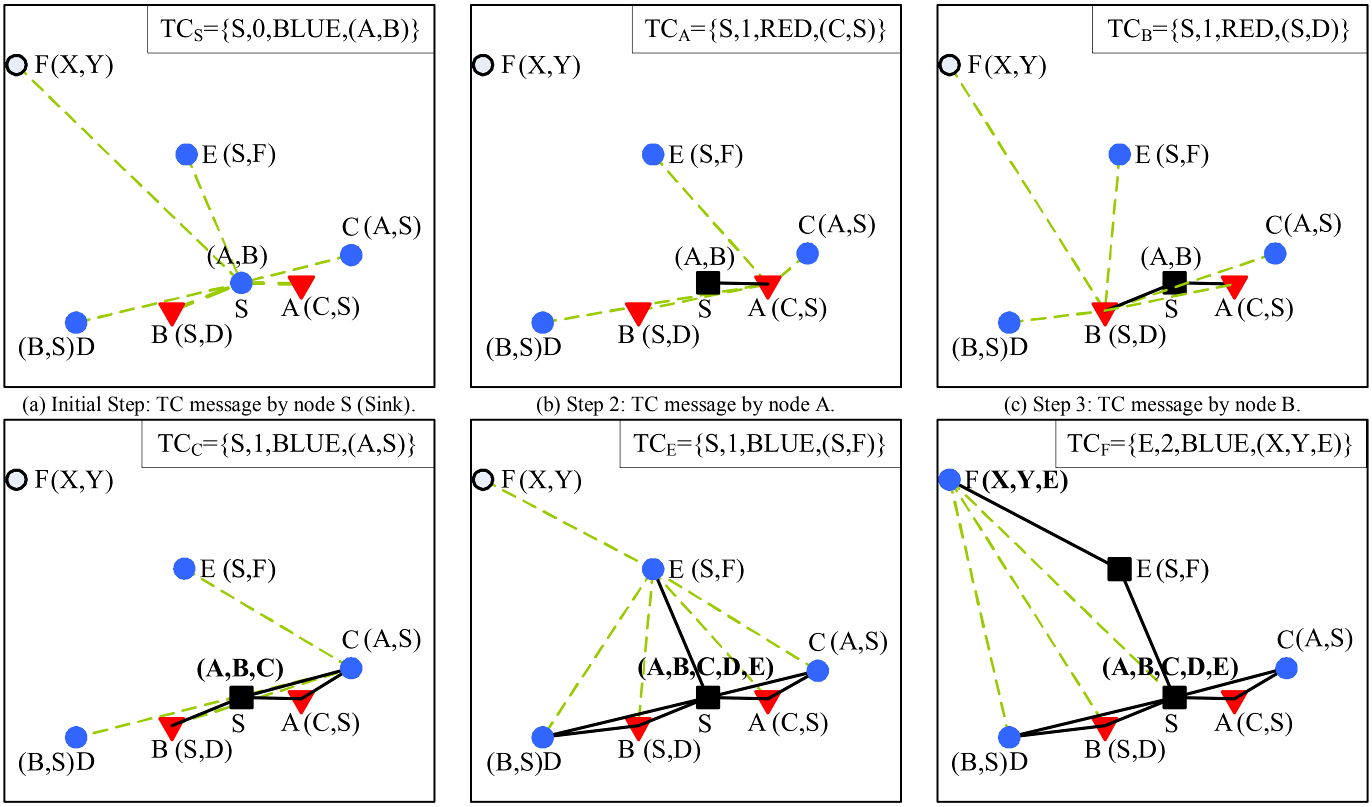
(a) (b)

Figure 1. Sample topology snapshots for 200 nodes: (a) Minimum Spanning Tree (MST), (b) k-Neighbor with k=9.

Most of the existing topology control proposals provide data traffic pattern independent assessments of their work where network-wide connectivity and minimizing interference are of foremost concern. The low complexity communication graph is obtained at the expense of inflexible or sub-optimal routing options. Usually the sparsest topologies, such as produced by the MST [6] algorithm result in longer path lengths, which do not scale well with the growing network size (see Fig. 1 (a)). In presence of multi-hop data traffic patterns, large number of hops will significantly degrade the overall network performance. In contrast to this, for the denser topologies, such as produced by the k-Neighbor protocol [2] the estimated number of neighbors to obtain a fully connected network is too large to minimize the energy cost (see Fig. 1 (b)). Moreover, for local communication that includes broadcasting of status information will produce significant interference among neighboring nodes in WSNs.

Typical data gathering applications for sensor networks utilize many-to-one traffic pattern in addition to the local and point-to-point communications. Therefore, it is critical to construct topologies which make services like converge-cast and aggregation efficient for better network performance. More recently, research efforts have been made to highlight these issues [7], [8]. However, no concrete algorithm is presented that can adapt itself for various traffic patterns.

In this paper, we propose the power control based approach to the topology management. Each node adjusts its number of neighbors so that a fully connected tree-like topology can be constructed towards the sink. We employ a performance knob *k* that enables the network designers to construct resultant topologies that can be optimized according to several traffic patterns. This flexibility in terms of topology resolution offers an efficient tradeoff between the available resources and the network topology complexity. The simulation results validate our claim that the proposed



(a) Initial Step: TC message by node S (Sink). (b) Step 2: TC message by node A. (c) Step 3: TC message by node B.

(d) Step 4: TC message by node C. (e) Step 5: TC message by node E. (f) Step 6: TC message by node F.

Figure 2. Diffusion process of TC message for k=2; with four types of information, of {Node-to-Sink, Hops-to-Sink, Color and N_i^2 } at $T_{\max}$.

framework shows a versatile performance for the given set of metrics.

II. Topology Management via Power Control

Our work implements a flexible topology management framework that constructs tree-like network topologies with reduced energy consumption. The basic idea is to employ the power control approach to the topology management where nodes are allowed to choose different transmission power levels. The proposed scheme selects a subset of nodes that forms a connected backbone of bi-directional links towards the sink. The members of this subset are colored BLACK whereas the other nodes are either RED or BLUE. Both RED and BLUE nodes are "associated" with the BLACK node (i.e., they maintain a bi-directional link), while BLUE nodes are also candidate BLACK nodes. Initially, all nodes are WHITE in color. As the algorithm proceeds, nodes change their colors according to their role. The algorithm operates in two phases.

A. Neighbor Discovery Phase

Initially, each sensor node *i* tries to discover its neighbors using a MAC layer beaconing at the maximum transmission power range ($T_{\max}$). A neighbor table (N_i^*) is maintained in non-decreasing order of the distance. Techniques that utilize different physical measurements such as Received Signal Strength Intensity (RSSI) [9] can be used to estimate the distance between two nodes.

B. Topology Construction Phase

The sink node initiates the topology setup phase by first turning itself to BLUE and by issuing a *topology construction (TC)* message at the maximum transmission power. Among other fields, the TC message contains a list of *k* least distant neighbors (N_i^k). These fields are modified and then subsequently broadcasted by all the other nodes only once. Upon receiving the TC message, each WHITE node *j* verifies whether they have *k-symmetric* link with the sender node *i*. If *i* and *j* are k-symmetric i.e., ($\{j|j \in N_i^k\} \wedge \{i|i \in N_j^k\}$), the receiver node becomes RED. In case of *k-asymmetric* link i.e., ($\{j|j \notin N_i^k\} \wedge \{i|i \in N_j^k\}$), the receiver turns BLUE otherwise the color remains unchanged.

Before a node disseminates its TC message further into the network, it has to decide on two aspects: the forwarding sequence and their color. We implemented a distance-based forwarding scheme with the help of a simple timer. This timer is set proportional to the distance from the sender node i.e., the closest receiver node forwards the TC message earliest. To ensure that each node disseminates the TC message only once, the timer value cannot be re-initiated by overhearing of subsequent TC messages. Moreover, this technique avoids collision among the contending neighbors as well.

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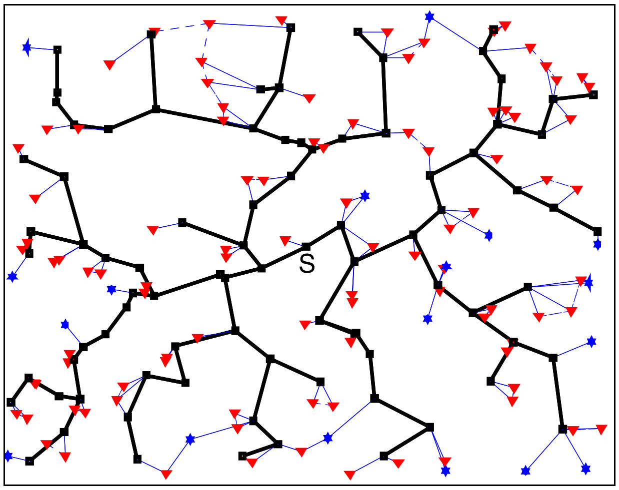


Figure 3. Sample topology snapshot for 200 nodes: Proposed framework with k = 2. Solid black lines represent connected backbone.

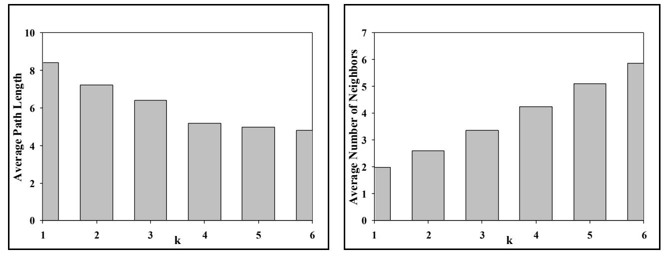
To exemplify these heuristics we consider a simple topology given in Fig. 2. Here, k is set to 2 and N_i^2 is shown in parenthesis besides each node i. The sink node S initiates the topology construction phase by broadcasting a TC message (represented by the dashed lines). The contents of the TC message are given at the upper right corner in each figure. On reception, all the neighboring nodes calculate the timer value to send their respective TC messages. Based on the estimated distance from the sender node, each node will calculate its forwarding sequence. In our example, the forwarding sequence is represented by the alphabetical order given as node IDs. Fig. 2 (a) shows the coloring of the nodes after the TC message is received by the neighbors from the sink node S. Since nodes A and B have 2-symmetric link with S, they turn RED (in triangle shape). Similarly, node C, D, and E will turn BLUE (filled circle) because of their 2-asymmetric links. Whereas node F's color remains WHITE (unfilled circle).

In order to construct a fully connected backbone, each node has to be associated with a special backbone node such that it guarantees a bi-directional link towards the sink. We call such a node as *Node-to-Sink*. For RED nodes this selection is simple, since they already have a symmetric link with the BLUE node. Fig. 2 (b) illustrates this process where node A selects S and send the TC message. This decision is conveyed to the other node while they overhear the TC messages. Once node S finds out that some other has selected it as *Node-to-Sink* it changes its color to BLACK (in square shape). In Fig. 2(c), node B repeats the same procedure.

For the given value of k, a node might have no k-symmetric neighbors, which may result in either a unidirectional link or the network partitioning. The BLUE node has a distinct characteristic i.e., it has a unidirectional link with a potential BLACK node. In order to make an optimal choice, it selects the least distant BLUE node. Once node j selects another node i as its Node-to-Sink, in order to guarantee a bi-directional link, i should also include j in its N_i^k even if it already has k-symmetric neighbors. Finally, the node i sets its transmission power to the level that is required to transmit packets to the farthest node in the *extended* N_i^k and changes its color to BLACK (if not already BLACK). In Fig. 2 (d), node C performs the above procedure with node S, followed by the node D and node E in Fig. 2 (e). The nodes retain bi-directional links with their k-symmetric neighbors.

In Fig. 2 (f), WHITE node F selects node E as its Node-to-Sink. Here, it is noteworthy that Node F turns BLUE and increments the Hops-to-Sink field by 1, before the TC message is sent. In scenarios where there exists no BLUE node, any least distant node which is minimum hops away from the sink is selected. So, we add one more piece of information in the TC message, namely *Hops-to-Sink*. Its value increment as the TC message is disseminated across the network. The forwarding sequence of the TC message ensures that this value is incremented properly.

Our approach results in a tree-like hierarchical structure, where RED and BLUE nodes are associated with the set of BLACK nodes by utilizing optimal transmission power levels. The BLACK nodes are connected directly with relatively larger transmission power, thus forming a backbone. Fig. 3 illustrates the sample topology snapshot for our proposed scheme with k set to 2. The number of links and nodes that are part of the backbone must be close to an optimal value according to the certain application requirements. In order to control the cardinality of BLACK nodes and the number of links associated with the backbone, we have utilized value of k as a control knob. As we will see in the next section, that the value of k determines the tradeoff among various performance parameters. The advantage of having such a communication structure is that it also constructs implicit data forwarding hierarchy towards the sink. Whereas the message complexity is equals to the network size (i.e., only one message per node).



(a) (b)

Figure 4. Evaluation of (a) Average path length and (b) Average number of neighbors, for various values of k.

III. PERFORMANCE EVALUATION

A. *Simulation Environment*

Our evaluation combines average path length toward the sink with the number of contending neighbors and average energy cost. A performance knob k is used to study the tradeoff among these aspects while a connected backbone of bi-directional links is built. We have performed simulation, using NS-2 [10] simulator. In our simulation model, 200 nodes are placed randomly over a 1000x1000m^2 area, with the sink node positioned at the center. The maximum transmission range is set to 250 m. For a comparative study, we consider

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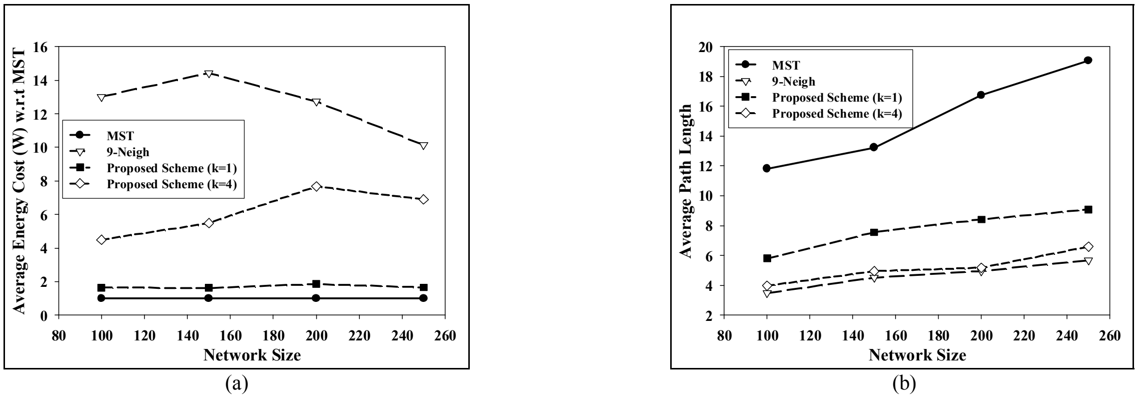

Figure 5. Comparison among Proposed framework with k=1 and k=4, 9-Neigh and MST generated topologies for various values of network size. (a) Average energy cost w.r.t MST and (b) Average path length.

the Minimum Spanning Tree (MST) and k-Neighbor topology control protocols. Following two metrics are used for performance evaluations. (1) *Average Energy Cost,* is the ratio between the powers assigned to all the nodes, which is obtained at the end of the topology construction phase and the network size. (2) *Average Path Length,* is defined as the ratio between total number of hops and the network size.

B. Simulation Results

Fig. 4 (a) and (b), show the average path length and average number of neighbors for various values of k, respectively. For higher values of k, the nodes tend to operate at larger transmission power levels, resulting in fewer hops towards the sink. However, an opposite trend is observed in terms of number of neighboring nodes. As the value of k grows, a denser communication graph starts to appear, thus showing more topological details. Intuitively, the value of k acts as the control knob.

Finally, we compare our scheme for k set to 1 and 4 with MST and the k-Neighbor protocols. In the k-Neighbor protocol, we set the value for k to 9 (i.e., 9-Neigh) which guarantees a fully connected topology. In this set of simulation results, the network size n is varied from 100 to 250 in increment of 50 nodes. Fig. 5 (a), show the results for average energy consumption which are normalized with respect to the values obtained for the MST. The cost for maintaining a fully-connected topology is highest for the 9-Neigh protocol, where as MST consumes least amount of energy. For lower value of k (i.e., k=1), the proposed scheme performed comparable to that of MST. For the intermediate value of k (i.e., k=4), our scheme performance is in the middle between the two extremes of MST and 9-Neigh. Fig. 5 (b) plots the average path length for all the schemes. Lower energy consumption in MST cost this scheme in term of average path length. Presence of non-local data traffic can reap away its previous advantage over other schemes. The 9-Neigh scheme performed the best, at the cost of higher energy consumption and contending neighborhood. Our scheme with higher k value perform almost identical to the 9-Neigh with much less energy cost. For the lowest value of k the performance of our scheme lies in the middle for the sparse networks.

IV. CONCLUSION AND FUTURE WORK

In this paper, we propose a power control-based topology management framework for WSNs, which constructs a backbone of bi-directional links towards the sink. Unlike most of the previously proposed schemes, our work constructs topologies at various levels of details by employing a control knob *k*. Simulation results show that by tuning this knob, we can satisfy various data traffic patterns with diverse performance requirements. For example, the higher values of k results in fewer number of hops and thus favor applications with moderate percentage of data traffic targeted towards the remote destinations. There are several avenues in our research that will be addressed in our future work. The foremost is the theoretical analysis of the algorithm in terms of message and time complexity. Secondly, in order to judge the merits and demerits of each resultant topology we are performing extensive simulations in presence of real data traffic.

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