Localized Topology Generation Mechanisms for Wireless Sensor Networks

Congzhou Zhou and Bhaskar Krishnamachari
Department of Electrical Engineering, University of Southern California
Los Angeles, CA 90089, U.S.A.
{congzhoz, bkrishna}@usc.edu

Abstract— **The basic topology desired in data-gathering wireless sensor networks is a spanning tree, since the traffic is mainly in the form of many-to-one flows. Nodes in the network can self-configure themselves into such a topology by a two-phase process: a flood initiated by the root node, followed by parent selection by all nodes. We present four localized topology generation mechanisms – earliest-first, randomized, nearest-first, and weighted-randomized parent selection. We also compare the network performance of these mechanisms on the basis of the following metrics: node degree, robustness, channel quality, data aggregation and latency; our study shows how localized self-configuration mechanisms can impact the global network behavior.**

Key word: wireless sensor networks, parent selection, information extraction, spanning tree, aggregation tree, and localized/global network topology generation.

I. Introduction

A wireless sensor network is essentially a distributed collection of nodes, each capable of sensing, computation, and RF communication. Recent advances in wireless communication, computing and MEMS technologies have made tiny, smart, and inexpensive nodes possible. We can envision that in the near future wireless sensor networks composed of hundreds or thousands of these devices will be used for many applications such as perimeter surveillance, structural health monitoring, tracking of accidental chemical leaks and spills, etc. [1,5,10].

While structured deployment (with careful placement of nodes and pre-configured topologies) is a possibility in some applications, other applications require unattended, ad-hoc deployment in remote or hostile environments. We consider a scenario in which a large number of sensor nodes are deployed (for example scattered/dropped from an aerial vehicle) in some "operational area." Because of the scalability requirement and the requirement of unattended operation in remote or hostile environment, this sensor network must be **self-configurable**. Our primary focus in this paper is on the self-configuration of the network topology.

For data-gathering applications, in which the typical traffic is many-to-one, the basic sensor network topology that is desired is a spanning tree. This tree can be constructed by a two-step process: the outward flooding of a discovery message, followed by a phase in which all nodes select a parent based on the messages they received. Note that this simple tree construction process has the benefit of being completely *localized*, leading to a scalable design.

In this paper, we first describe four topology generation mechanisms: earliest-first, randomized, nearest-first, and weighted-randomized. These localized mechanisms differ in the manner in which the parent selection takes place and result in qualitatively different tree structures. We show that one significant graph-level metric that distinguishes these mechanisms is the variance of the node degree. We next evaluate these four mechanisms based on four network performance metrics: robustness, channel quality, data aggregation, and latency. Our primary objective is not finding the "optimal" mechanism, since there is no single strategy that performs equally well for all metrics; rather, our contribution is to analyze and evaluate how the different localized topology generation schemes can impact global network performance.

The rest of this paper is organized as follows. Section II discusses some related work. Section III introduces the four mechanisms in constructing the network topology. Section IV discusses the metrics used in the evaluation. Section V provides the setup of simulation and its results. Conclusions and future work are presented in Section VI.

II. Related Work

Much research has been conducted in sensor networks involving all levels from physical layer up to the application layer during the past few years. Paper [8] summarizes those previous research and concurrent work on protocol and algorithm designs in sensor networks. For example, [12] presents a new MAC layer protocol and [4] proposes a network layer protocol both for the purpose of energy conserving.

Broadcasting in wireless sensor networks is a very common operation. The easiest and most straightforward way to do broadcasting is by flooding. However, [11] studies the broadcast storm problem and shows that flooding is very costly in terms of energy and can result in serious redundancy, contention, and collision. It also proposes several schemes to alleviate this problem. Since only one flooding message is needed at the beginning of the topology construction (to insure connectivity), its negative effect is negligible.

One of the most important tasks in wireless sensor network is information extraction. Due to finite energy resources, this data gathering process must be energy-efficient in order to extend the lifetime of the network. Paper [2] models and analyses data-centric routing protocols, showing that the energy gain due to data aggregation is significant but may result in high latency.

In this paper we are interested in the effects of localized topology generation mechanisms on network performance. A couple of these mechanisms were first suggested in [6,7], without details or evaluation. Finally, we should mention that we are focusing on the fundamental structure of the network, and hence do not consider lower-level protocols, such as the MAC protocol.

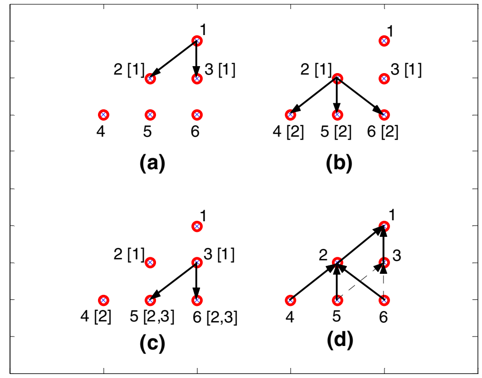

Figure 1. Phase I: flooding. This phase includes (a), (b), and (c). The flooding message is propagated throughout the network. Note the number in the bracket represents the parent candidate; Phase II: parent selection. After flooding, every node will select its parent from its parent candidates according to some parent selection mechanism. (d) shows one possible result. Note that in (d) the solid lines represent the selected parents and the dashed lines represent other possible choices.

III. Parent Selection Strategies

At the beginning of the topology generation process, the sink/base station (node 1 in Figure 1, 2, and 3) will flood the discovery message after node deployment. Upon receiving the flooding message for the first time, every node will rebroadcast the flooding message as shown in Figure 1(a), (b), and (c) in sequence. A node may get more than one flooding message but it will only choose the upper level node to be its parent. The information about node level, ID, and some other aspects is encapsulated in the flooding message and every node can extract and store that information locally. Therefore, after the flooding, every node knows the information about its immediate neighbor nodes and then performs parent selection based on that information. Figure 1(d) gives one result after the parent selection: node 4, 5 and 6 select node 2 as their parent and node 2 and 3 both select node 1. In this section, we present four localized strategies that can be used for parent selection: the earliest-first, randomized, nearest-first, and weighted-randomized schemes.

Earliest-first parent selection: In this scheme, each node will choose as its parent node the one from which it receives the first flooding message. This scheme is the simplest to implement. A node that broadcasts the flooded discovery message first will be selected as parent node by all its neighbors at the next level (i.e. that are one more hop away from the base station). Consider the illustration in Figure 2(a); say node 2 broadcasts before node 3. Then node 4, 5, and 6 all choose node 2 as their parent.

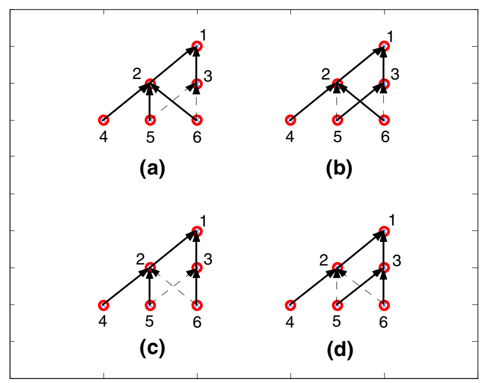

Figure 2. Illustration of possible results from the four parent-selection based topology generation schemes. a) Earliest-first b) Randomized c) Nearest-first and d) weighted-randomized.

Randomized parent selection: In this scheme, the node will randomly choose its parent node from all possible candidate nodes with equal probability. Nodes 5 and 6 both have the same parent candidates, nodes 2 and 3, as illustrated in Figure 2(b) and they make independent random decisions. Since every candidate has an equal chance, the node that broadcasts first will no longer be the only one selected.

Nearest-first parent selection: The node will choose the nearest candidate node to be its parent. Intuitively, this should result in better channel quality on all links, assuming all nodes have the same transmitting power. We can use the received signal strength indicator (RSSI) to estimate the distance [9].

Figure 2(c) illustrates the spanning tree obtained by using this nearest first strategy.

Weighted-randomized parent selection: In this scheme, each node assigns a weight to every possible parent node according to their number of neighbors. The parent selection is randomized with these weights. A node with more neighbors will get smaller weight and is less likely to be selected. In Figure 2(d), node 2 has 5 neighbors and node 3 has 4 neighbors, so node 3 gets higher weight and has higher probability to be chosen as nodes 5 and 6's parent than does node 2. This scheme attempts to balance the number of children per parent node.

IV. Metrics

In this section, we describe five metrics used to compare the topology generation strategies described in section III. They are node degree, robustness, channel quality, data aggregation, and latency.

Node degree: This is the number of children every node has. It is a way to distinguish the resulting global topologies from a graph theoretic perspective. While it is not directly a network performance metric, we found the variance of node degree highlights the topological differences between the different schemes.

Robustness: This metric is the percentage of network that is still connected after a node failure. A node failure results in additional network overhead for repair, and temporary disconnection of nodes. We assume that the probability of a node failure is related to the node's usage.

Channel quality: Radio signal strength decays exponentially as it propagates. We express that as:

$$E_r \propto \frac{1}{[d(t,s)]^K} E_t \qquad (1)$$

where E_r and E_t represent the signal strength at receiver and transmitter site respectively, *d(t,s)* is the Euclidean distance between receiver and transmitter, and the exponent *K* is an environment-dependent parameter (chosen to be 4 in our simulation). Next we define channel quality as the channel **bit error probability, P**. Assume using on-off signaling [3],

$$P = Q\left(\sqrt{\frac{E_r}{N}}\right) \qquad (2)$$

where N is channel noise energy. In our simulation, we let N=0.01.

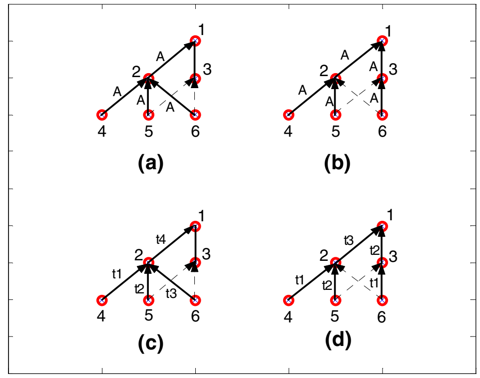

Figure 3. (a) and (b) show the data aggregation, (c) and (d) show the latency for two different tree structures. Note that in this figure "A" means the desired information by node 1, and "t1, t2, t3, t4" represents the time when the transmission occurs. "t1" is the earliest time and "t4" is the latest time. This figure shows that a more clustering tree may do better data aggregation but may encounter longer latency.

Data aggregation: If an event occurs, every node within the sensing range of that event will detect it and report to the sink. Since in most situations, every node will report the same information, the intermediate nodes can eliminate the redundancy, minimize the number of transmissions, and hence save energy. A node with more children can do better aggregation. In Figure 3 (a) and (b), if nodes 4, 5, and 6 detect the same event and report to node 1, the total number of transmissions required after data aggregation is equal to the number of edges in the minimum number Steiner tree in the network which contains the node set (1,4,5,6) [2]. In this case, the total number of transmissions for (a) is 4 and 5 for (b).

Latency: We assume that there are sufficient communication channels to choose from and each node has only one transceiver device. Therefore, multiple unique pairs of transceivers can communicate simultaneously, but if more than one node wants to transmit to the same receiver node, the transmissions must be made one at a time. The latency we measure is the total time from the occurrence of the event to the reception of the message by the sink. For example, in Figure 3(d): at time t1, node 4 transmits to node 2 and node 6 transmits to node 3; at time t2, node 5 to 2 and node 3 to 1; at time t3, node 2 to 1. Hence the latency is 3 units of time. In Figure 3(c), similarly the latency is 4.

V. Simulation Experiments and Results

In the previous two sections, we have described four localized topology generation mechanisms and five metrics used to evaluate them. In this section, we introduce our simulation experiments.

We uniformly place 100 static nodes in a 1 x 1 square area. All nodes in the network have the same communication range R. The sink is located at the left lower corner and the event is located at the center of the grid space. We define the sensing range to be 0.15 so that at least 3 sensor nodes are within that sensing range of the event. For information extraction measurements, data aggregation and latency, all data from those nodes need to be collected and transmitted to the sink.

We first find the minimum communication range (Rmin) to connect the network, and vary the communication range from Rmin to 2.5Rmin. The simulations are all averaged 20 times for each scheme. Figures 4 through 8 present the simulation results.

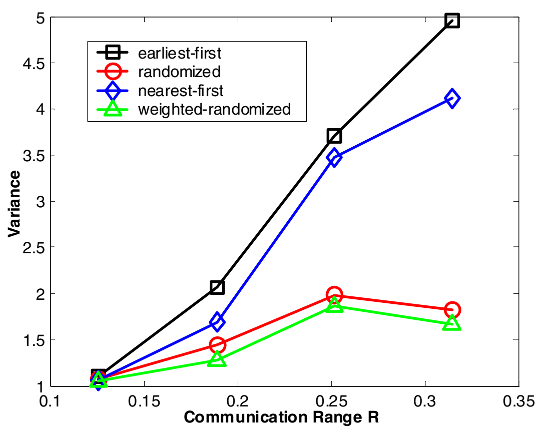

Figure 4. Variance of node degree: Note that in this Figure, the difference of variance for four schemes becomes larger when the communication range R increases (i.e. when the density is high).

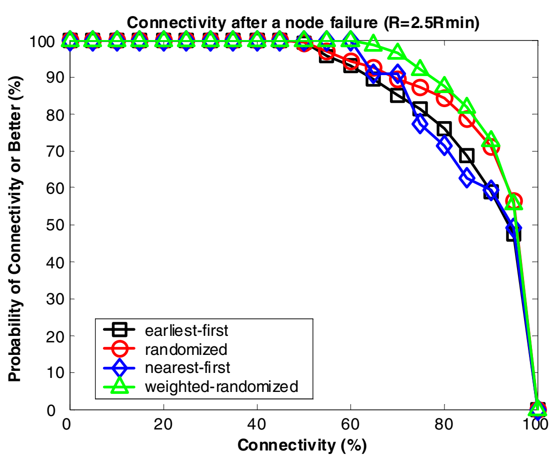

Figure 5. Robustness: The probability that at least that percentage of nodes is still connected to the sink after a node failure.

Figure 4 shows the variance of node degree for different schemes. We can observe that the difference between node degree variances of the schemes increase as the communication range is increased. The earliest-first scheme has the highest variance and the weighted-randomized scheme has the lowest variance.

Figure 5 shows the robustness of the network. The randomized and weighted-randomized schemes are more reliable than the earliest-first and nearest-first schemes when the communication range is large.

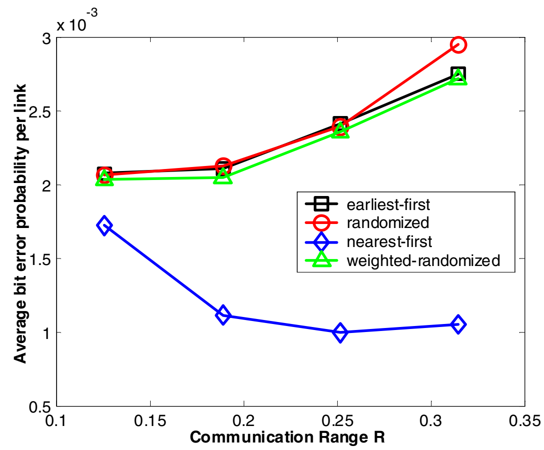

Figure 6. Channel quality

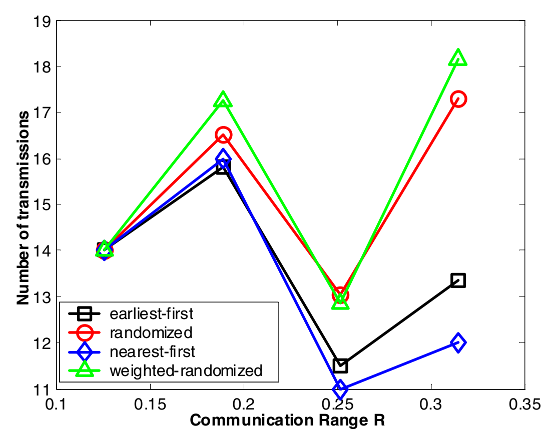

Figure 7. Data aggregation

Figure 6 shows that the nearest-first scheme has the lowest bit error probability among all four schemes. This is because the nearest-first scheme prefers high-quality, short distance links.

Figure 7 shows the data aggregation in terms of number of transmissions needed to report an event. In earliest-first and nearest-first schemes, more data can be aggregated than in randomized and weighted-randomized schemes, which suggests more energy conservation in earliest-first and nearest-first schemes.

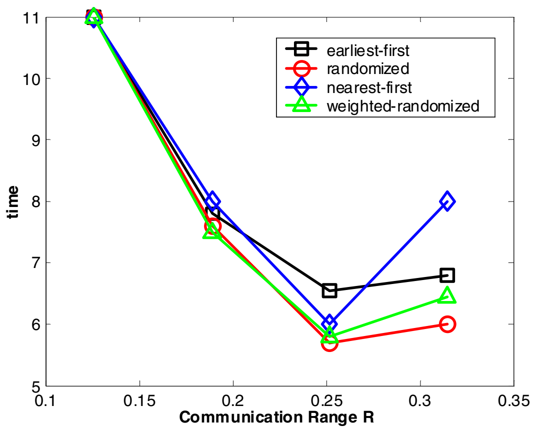

Figure 8. Latency

Finally, Figure 8 displays the results for the latency. The randomized and weighted-randomized schemes have shorter latency than the earliest-first and nearest-first schemes, suggesting quicker information extraction in randomized and weighted-randomized schemes.

VI. Conclusions and Future Work

This paper examined the effect of localized topology generation mechanisms on network performance metrics. We presented four mechanisms – earliest-first, randomized, nearest-first, and weighted-randomized – and several metrics to evaluate them. Through simulation, we have shown that localized parent selection strategies can significantly impact the global performance of the network in different ways.

To summarize our observations from the simulation results, we found that the earliest-first and nearest-first schemes produce a data-gathering tree with low network reliability, high data aggregation ability, and long response time to an event. Randomized and weighted-randomized schemes, on the other hand, construct a balanced data-gathering tree with high network reliability, low data aggregation ability, and short response time to an event. In addition, nearest-first scheme outperforms other three schemes in channel quality. In all cases the differences in performance are exaggerated most when the communication range is large (when the densities and therefore possible choices for each mechanism are high). There is another interesting observation. From Figures 7 and 8, we find that when R=2Rmin, the number of transmissions needed is the lowest and the latency is also the shortest for all four schemes. This observation bears further study.

In this paper, we only consider the network consisting of 100 nodes. In the future work, we will analyze large-scale networks (e.g., more than 1000 nodes), and other node placements. There are also other dimensions in which our paper could be extended, such as the incorporation of richer models for studying data aggregation and latency, and an analytical study of the parent selection schemes.

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