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A numerical study of energy consumption and time efficiency of sensor networks with different structural topologies and routing methods

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ABSTRACT

This paper reports a numerical study of energy consumption and time efficiency of sensor networks with five different structural topologies and four different routing methods, regarding their performances and costs, which might provide some references and guidelines for designing sensor networks under various conditions for possible applications.

1. Introduction

Complex networks, deferring from traditional regular or random networks, have more complex architectures in general [1]. Recent work on analyzing network structures has found that many real-world networks are small-world networks or scale-free networks because the statistical analyses of many real datasets highly fit to such mathematical models. Watts and Strogatz [2,3] found that many networks have a common feature from the small-world model. Barabás and Albert [4] mapped the topology of the World Wide Web to a scale-free model. Faloutsos et al. [5] showed that some power-law relationships exist in the Internet topology. Jeong et al. [6] found the large-scale organization of metabolic networks to follow a power-law in node-degree distribution. Newman [7] pointed out that the structure of scientific collaboration network also has a scale-free degree distribution. These coincident findings in various disciplines provided great insights to and confidence on further studying more general mathematical network models which, in turn, offer useful tools for in-depth studies of real-world networks regarding their degree distributions, average shortest paths, cluster coefficients, community structures, Laplacian spectra, and so on [8–12].

In addition to the aforementioned common structural features, many complex networks share another feature that the nodes are resource-limited. Examples include the Internet which consists of finite-buffer network devices, cooperation networks which are composed of time-limited people, and wireless sensor networks which are constituted of self-powered sensors. Therefore, studying resource-limited networks is quite important from an engineering point of view. In this paper, wireless sensor network is chosen as a reprehensive to investigate its energy consumption and lifetime performances in common interest.

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A wireless sensor network consists of many small sensors distributed in a certain space. Usually, there is a sink node in the network. The sink node typically is a base station, which directly connects to the entire fixed network. The other sensors are equipped with wireless transmitters, receivers and batteries, which communicate with each other so as to pass their obtained information to the sink node. Wireless sensor network has a broad spectrum of applications in the military and industries. Some wireless sensor networks are built to collect information (for example in battlefields), some are used to monitor the environmental conditions, and some are used to keep the buildings safe, etc. Since the energy used by most nodes is provided by batteries, how to save energy during operations becomes a critical issue in the design of a sensor network. In the current research, main focus is on efficient routing methods for wireless networks. Several energy-saving methods were proposed to optimize the information transmission processes between different layers in the network protocol stack [13–16], for example on the physical layer and the MAC (media access control) layer. It was pointed out in [17] that "many energy-efficient routing protocols tend to minimize energy consumption on forwarding paths, but if some nodes happen to be located on most forwarding paths, their lifetime will be reduced." That means the topology of the network may have significant influence on the lifetime of the nodes.

Motivated by the above observations and research advances, this paper aims to simulate and analyze the energy consumption and lifetime performances of various sensor network models by combining the network topology and the routing methods together, trying to further understand their mutual effects on the performances especially the lifetime of the senor nodes. Meaningful findings could be summarized into some rules for designing more efficient and more robust wireless sensor networks with different types of topologies and their corresponding routing schemes. It is also expected that the approach to be developed in this investigation will not only be applicable to wireless sensor networks, but could also be applied to other types of complex networks with similar topologies and behaviors such as local area networks in the Internet and some time- or energy-limited social behaviors in the human society.

In the rest of the paper, several network models with different topologies and different routing methods for information transmission are studied. More specifically, random-graph networks, navigable small-world networks, scale-free networks, and grid networks, are simulated and compared on four routing schemes based on shortest path forwarding, broadcasting, memoryless random walk and random walk with memories.

2. Network models

In this section, network models and routing methods to be studied are detailed, with network parameters defined and evaluation metrics specified.

2.1. Network models

Only undirected, unweighted and initially connected networks are considered. Thus, the size of a network is the number of connected nodes in the network.

ER Random-graph model [18]: Start from N isolated nodes. For every possible pair of nodes, use a probability $p \in (0,1)$ to connect them together. This operation is performed once and once only. The resulting network is a random graph of N nodes with $pN(N-1)/2$ edges (an expected value). For such networks, the node degrees are homogeneous, following a Poisson distribution.

Kleinberg small-world model [20]: Start from a standard planer square lattice. For every possible pair of nodes, use probability $p = 1/d^2(u, v)$ to connect them together, where $d(u, v)$ is the distance between nodes u and v. This operation is performed once and once only. The resulting network is a so-called navigable small-world network, with a small average path-length (bounded by $\log(N)$, therefore search can be done in polynomial time), large average clustering coefficient and a homogeneous node-degree distribution.

It is noted that the small-world network model has three variants [1–3,20]: Watts–Strogatz, Newman–Watts and Kleinberg models, among which the Kleinberg model has a structure that can facilitate shortest-path search therefore is more appropriate for this paper to use in simulations regarding network energy consumption and time efficiency.

Scale-free model [4]: Start from a (small) fully-connected network. At every step, one new node is added to the network and the new node is connected to every old node with a probability proportional to the degree of that old node (the so-called preferential attachment principle). The resulting network has a heterogeneous node-degree distribution in the power-law form. This is a growing network with the power-law being independent of the scale of the network (the so-called scale-free property).

Grid model: This is a standard planar square lattice.

2.2. Routing methods

In a wireless sensor network, after a sensor detects some information or collects some data, it needs to pass the information or data to the sink by a certain means, typically through one of the following four types of routing schemes.

Shortest-path forwarding: The sensor node will pass the information to the sink by using shortest-path forwarding. In this process, other than this sensor, all the sensors which help in passing the information through the shortest path to the