A Small-World Routing Protocol for Wireless Sensor Networks

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Abstract—In this work, we propose a new routing protocol—the Small-World Routing protocol. With the idea originating from the small-world theory, the proposed protocol finds paths between the queries and events through recurrent propagations of weak and strong links. The operation of the protocol is simple and does not require much computational power. We evaluate the performance of the proposed protocol through extensive simulations. The results indicate that the proposed protocol, when compared to rumor routing protocol, can find much shorter paths (and thus lower power consumption during data delivery) with much higher successful rate.

Keywords—wireless sensor networks; small world; routing protocols; power saving

I. INTRODUCTION

Wireless sensor networks [1, 2] are networks comprising a large number of small size and low cost sensing devices, which are densely deployed onto some area of interest through any viable approach. Every sensor may be designed to detect various kinds of signals (e.g., temperature, humidity, luminosity, or voice) and then relays the collected information to the query nodes by propagating hop-by-hop through intermediate sensing nodes within its communication radius.

The characteristics of sensor networks make themselves suitable for data collection over/within regions that human being are unable or hard to reach, for examples, battle fields reconnaissance, disaster (such as earthquake, fire, etc) areas monitoring [1, 2]. With sensor networks, geographic barrier may be overcome and real-time data can be collected so that proper measure can be taken accordingly. In addition, the sensor networks may also find applications in areas like patient monitoring, inventory management, product quality monitoring, etc [1, 2].

Sensor networks usually connect to the outside world through the so called sinks (may be regarded as gateways). All data collected by sensor nodes are sent to the sink, and then the sink relays such data to remote users or servers through the Internet, satellite, or any viable medium. Accordingly, a fundamental issue in sensor-network applications would be how an event (e.g., information) being detected promptly by neighboring sensor node and relayed hop-by-hop to the interested query node, which, in fact, is a routing problem. However, the sensor network routing problem may be distinct in that it is constrained by the following two factors: (1) limited and non-rechargeable battery power, and (2) minimum computational power and storage, of the sensor nodes. Consequently, a routing protocol for the sensor network needs to be simple and power efficient so that it does not impose too much burden on sensor nodes and will not consume too much of their limited battery power. In addition, the routing protocol also needs to find shorter paths between the query request and event as long as possible. A shorter path implies that less number of nodes is involved, which is more essential in case the transmission is going to last for some period of time.

In this work, we propose a new routing protocol that based on the small-world theory, and thus is called the small-world routing protocol. The proposed protocol finds paths between the queries and events using recurrent propagations of weak and strong links. According to our simulations, with comparable cost and comparable (or better) success rate in route construction, our protocol is able to find paths for query and event that contain less intermediate sensor nodes as compared to the other notable routing protocol, in particular, the rumor routing protocol.

The rest of the paper is organized as follows. In Section II, we will review related work in the field of sensor-network routing. A brief introduction to the small-world theory will be given in Section III, followed by presentation of our proposed small-world routing protocol and its variations. Simulation settings and results will be described in Section IV. Finally, we will list possible future research directions and conclude this paper in Section V.
II. RELATED WORK

Flooding [6] was one of the earlier mechanisms used to propagate information collected by sensor nodes in the sensor network environment. With flooding, sensor node that detects the occurrence of an event broadcast such information to every node in the network. Similarly, in case a node needs to acquire some information, it also floods such query to all the other nodes. The above two scenarios are called event flooding and query flooding, respectively. Usually, flooding is able to find the shortest path, but may also consume more power and bandwidth as a result of broadcasting storm.

To preserve power consumption, rumor routing was proposed [7]. With rumor routing protocol, when a node detects an event occurrence, it relays this event to a randomly selected node through the use of agents. Nodes that such agents go through would record related information and form a path. For a query request, similar procedure is executed. In case both paths intersect, a communicating path between the event and query nodes is established.

The drawback of rumor routing is that routes established are usually not the shortest ones, which may result in higher transmission loss rate. It is also possible that spiral-like routes may occur or query may fail to find the event. Zonal rumor routing (ZRR) is the protocol designed to cope with these issues. ZRR protocol operates by dividing the network into zones so that agents can be forwarded zone by zone to spread event information to larger part of the network [8]. In case the zone size is partitioned properly, the ZRR protocol can achieve high query delivery rate with energy efficiency. On the other hand, inadequate zone size and uneven node density distribution may also degrade its performance. In addition, ZRR may not necessarily find the shorter path, either. ZRR also consumes additional time and power during the zone partitioning phase and requires more memory spaces for storing node information within a zone.

Straight line routing (SLR) [9] is also designed to fix the spiral-like routing path problem. SLR operates in a hop-by-hop fashion, however, instead of randomly searching for the next node, agents in SLR try to forward packets with a fixed direction as long as possible. To achieve that, computation is required in every move to search for the next node. In the worst case, the computation may not come up with any feasible next node.

Along & across routing algorithm proposed in [10] makes use of a hop tree structure, which works by maintaining hop levels with respect to a random root node. Events are routed along hop levels, while queries are routed across hop levels to seek for a match. The algorithm relies on broadcast to construct the hop level information at start, and requires consistent efforts (and thus precious battery power) to maintain such information as the algorithm proceeds. Although the algorithm guarantees to find path between query and event, however, this path is usually not the shortest one. In some worst cases, the path may circle along the same hop level.

A protocol that may somewhat related to the small-world idea is the so called random walks protocol [11]. However, the sensor-network routing problem that it addresses is quite different from our work. It focuses on finding multiple paths between a source and destination while the position of the destination is known. Consequently, the protocol requires the integration of GPS feature into the sensor nodes, which may not be cost effective for common sensor network applications.

The above mentioned protocols either trade energy for shorter path, or vice versa. In other words, ones that are able to find shorter path may consume too much battery power. On the other hand, ones that are energy efficient may not usually find the shorter path.

III. THE SMALL-WORLD NETWORK AND SMALL-WORLD ROUTING PROTOCOL

This section describes the intuitive idea (basing on the small-world network concept) behind the proposed routing protocol and explains how to fit the small-world network concept into the protocol.

A. The Small-World Network

The term small world network, was first mentioned by Watts and Strogatz [12] in their paper published in 1998. A small world network can be used to model the relationship among people, in which nodes may represent people and edges connect people that know each other. Most often people get acquainted with others that are neighboring to them (we refer it as strong link), while occasionally know friends that are far away (we refer it as weak link). Strangers can then be got linked by a mutual acquaintance and captured by the so called small world phenomenon. Sociologists have found that any given two persons, no matter how far away they are, can usually be related within six steps (and thus the term six degrees of separation). The key lies in the use of weak links, with which people can often relate themselves to ones that are distant away.

The small-world network is closely related to random graphs and regular graphs [13]. With a random graph, edges from a given node are randomly connected to the other nodes. On the other hand, in a regular graph, edges from a node always link to nodes that are of fixed distance away. The small-world network is one that has its characteristics in between both, with part of the edges connect regularly to nodes of fixed distance while others randomly to nodes that are quite far away. When it comes to the solutions to the sensor network routing problem, it appears that the flooding and rumor routing protocols can be analogous to the regular and random graph, respectively. It is thus interesting to explore whether the small-world network, like its regular and random counterparts, can also play a role in finding routes in between the query and event nodes in the context of sensor networks.

To map the small-world theory onto the sensor networks routing problem, we first regard the query or event node as a person, and the path connecting the two nodes as relationship between the two persons. We then let the agent program searches for a potential path by choosing partly some nearby nodes and partly some other randomly selected nodes that are located farther. Since the randomly selected nodes are usually not within the (broadcast) communication range, rumor routing or line rumor routing is used instead. Accordingly, the resulted
protocol is similar to a combination of broadcasting tree and rumor routing. We refer to the routing protocol the Small-World Routing Protocol (SWRP).

B. The Small-World Routing Protocol

In the following sub-sections, we describe how we implement the idea mentioned above.

1) Simulating the strong and weak links

With the SWRP, when the agent program is searching for a path, it partly selects routes that are via some (α) nearby nodes and the other via some (β) nodes that are arbitrarily hops away. Accordingly, α and β represent the number of strong and weak links of the Small-World network. However, it may not be possible that sensor node communicates directly with nodes many hops away and are not within its communication range. Alternately, we use routes that go through a number of hops to simulate the weak links. A new parameter, γ, is defined to represent the number of hops that a weak link contains. For subsequent steps, the same search sequences (with α strong and β weak links) are repeated. As a result, an additional parameter, H, is used to represent the number of occurrences that a particular search process may take.

![Diagram](image)

Figure 1. An example showing a scenario of the Small-World Routing process (with α=2, β=1, γ=2, and H=2 for the query).

Figure 1 illustrates the relationship of the above mentioned parameters: α, β, γ, and H with an example. In Figure 1, a query is searching for a potential event from the left. In each occurrence of the search step, there are 2 strong links (depicted in solid lines) and 1 weak link (depicted in dotted lines). The hop count, γ, of β is 2, meaning that each weak link in fact goes through two hops. For the search propagating process, the query steps are repeated two times. Accordingly, H value is two for the query process. Note that in a special case when α=0, the Small-World Routing Protocol is in fact equivalent to the rumor routing protocol with β being the number of agents.

2) Variations of the SWRP

The end nodes of the strong and weak links of the original SWRP design will recurrently expand more strong and weak links of themselves. Given a combination of α, β, γ and H parameter values, the searching tree may expand very quickly and generate too many broadcast messages during the path discovering process. As an illustration, let refer to the event routing in Figure 1, the number of broadcasts (to its neighbors) can be deducted and calculated as follows.

1) In case H=1, the number of broadcasts $N_b = β \times γ$ (1)

2) In case H=2, there would be $β \times γ$ broadcasts and $(α+β)$ branches for the first phase, and each branch generates additional $(β \times γ)$ broadcasts in the second phase. The total number of broadcasts would then be:

$$N_b = (β \times γ) + (α+β) \times (β \times γ)$$

(2)

3) In case H=3, there would be $(α+β)^2 \times (β \times γ)$ broadcasts in the third phase, which make the total number of broadcasts equivalent to:

$$N_b = (β \times γ) + (α+β) \times (β \times γ) + (α+β)^2 \times (β \times γ)$$

(3)

It can be easily seen that when $H=n$, the total number of broadcasts is then:

$$N_b = (β \times γ) + (α+β) \times (β \times γ) + (α+β)^2 \times (β \times γ) + \ldots + (α+β)^{n-1} \times (β \times γ) = \frac{(β \times γ)(α+β)^n - 1}{(α+β) - 1}$$

(4)

To reduce the number of growing branches (and thus the number of broadcasts), we can revise the operation of the original SWRP so that the agent can propagate along the search path in a more conservative and (hopefully) effective way. In the following, we will give two possible modifications of the original SWRP protocol.

First of all, we can limit the expansion of strong links. For example, limit the branching of strong links to only once in each search forwarding step. However, no limit is imposed on the growth of the weak links. The quick expansion as a result of the strong links is thus reduced. By limiting the strong links from further branching, the number of broadcast ($N_b$) in equation (2) and (3) now reduces to $β \times γ$ and $β \times γ \times β \times γ = (β \times γ)^2$, respectively. Accordingly, when $H=n$, equation (4) may reduce to:

$$N_b = (β \times γ) \times H$$

(5)

When compared to equation (4), the number of broadcast as depicted in equation (5) is greatly reduced.

In case that there is a need to further reduce the broadcast messages, it is also possible to set some constrains to the expansion of weak links. For example, in case β is originally set to 2, the branch of weak link is constrained to one after the first phase of expansion.

Note that the above two variations are only two of many potential possibilities of the SWRP protocol. These, together with the possible combinations of the original four parameters (α, β, γ and H), may well demonstrate how flexible our proposed SWRP protocol would potentially be.

IV. Simulation Results

We have designed and conducted a number of simulations to evaluate the performance of our proposed SWRP protocol and to explore how it performs under various parameters setting, e.g., varying α · β · γ and H. The simulation environment is specified by a 2000×2000 meters rectangular region with 1000 sensor nodes distributed randomly inside the region. The radio coverage range of each sensor node is assumed to be a circular area of diameter 150 meters, within which sensor nodes are able to detect the IDs and distance range of/to their neighbors. Two performance metrics, success rate in finding a path between the event and query and the average number of hop counts of the routing path, are of
interest in our simulations. In addition, routing cost characterized by the number of broadcasts is adopted as the basis for comparison. All results in our simulation represent averages of 500 test sample runs, with both the event and query nodes selected randomly in each run.

However, due to the page limitation, the following only show the comparison between the best performers of the SWRP and the rumor routing with 1 or 2 agents (referred to as RR1 and RR2). The results are shown in Figure 2. Legend appears in the figures, e.g., oS1.1.y.2, represents that protocol used is the original SWRP with $\alpha=1$, $\beta=1$, $H=2$, and $\gamma$ is regarded as a changeable variable. Similarly, vS4.1.5.h, indicates that protocol used is variation of the original SWRP with $\alpha=4$, $\beta=1$, $\gamma=5$, and $H$ is regarded as a changeable variable that varies with the routing cost.

In this paper, we adopt the idea of small-world theory and map it onto the sensor network routing problem. By simulating the strong link with one-hop short link and the weak link with multi-hop long link, we have developed the so called SWRP routing protocol. The operation of the SWRP protocol is characterized by four parameters, namely, $\alpha$, $\beta$, $\gamma$, and $H$. The SWRP protocol is very flexible since any change to one of the four parameters may potential change the route searching procedure. The simulations results shown in this paper may have demonstrated part of the above claim. More simulations and further researches should be conducted to evaluate the full potentiality of the SWRP protocol. In addition, exploration of how the four parameters affect the routing process and then modify SWRP so that it can meet all kinds of sensor networks routing environments and applications may be the other.

![Figure 2.](image-url)

**Figure 2.** Comparison of routing performance among variation and original SWRP and rumor routing. (a) success rate on event/query routing, (b) average hops between event and query nodes.

It can be seen that oS1.1.y.2/oS1.2.y.2 are in average approximately 1–3% lower in success rate. However, with that small margin in success rate, the average hop counts of oS1.1.y.2/oS1.2.y.2 are only half of that found with RR1/RR2. This demonstrates the superiority of the SWRP protocol, with which we can establish routing paths that are suitable for various kinds of concerns or applications. Not to mention that variation of the SWRP outperforms rumor routing in both aspects of routing metrics (see vS4.2.5.h and vS4.3.5.h). In particular, vS4.2.5.h can outperform RR1 or RR2 by (up to) 11% or 15% in success rate, and achieve that with (up to) 50 or 13 less in average hop counts.

### References