Abstract—In this work, we address the pass-over issue in wireless sensor network routing. Pass-over occurs when a query agent passes over an event agent even though the two lines cross each other, which may potentially prevent a query from finding the event. Even if the query and event agents eventually meet, the number of hop count may add up as a result of that. We tackle the problem with a variation of the Small-World Routing protocol (SWRP). The SWRP 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. It turns out that by maximizing the number of weak link of the SWRP within a controlled area, we may be able to reduce the possibility of pass-over. In fact, according to our simulations the pass-over can be completely excluded from occurring. Accordingly, the proposed solution not only cut the number of hop-count, but also achieve better successful rate in finding a route between the query and event. The corresponding wireless sensor network with the proposed routing protocol is thus more power conservative and lasts longer.

Index Terms—wireless sensor networks; small world; routing protocols; power saving.

1. INTRODUCTION

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]. As a result, sensor networks related issues, which include medium access control [1, 2], power saving [3], target tracking, routing [4], and network coverage [5], have been among the primary research focuses.

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, routing protocols for the sensor network need 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 addition to the above mentioned limitations, routing in a wireless sensor network may suffer from the so-called pass-over problem that is characterized by the scenario when a query agent and an event agent cross yet they fail to discover each other. Figure 1 depicts such an example where nodes that the query and event agents walk through are represented by $Q_i$ and $E_i$, respectively.

The pass-over problem was first addressed and partially resolved in [6]. However, the potential impacts on wireless
sensor network routing were not fully explored in their work. As a matter of fact, the pass-over effect may prevent a query from finding the event and thus has a negative effect on the successful routing rate. Even if the query and event agents eventually meet, the number of hop count, and thus the message delivery delay between the event and query may add up as a result of that. Moreover, due to the fact that more nodes involve in the routing process the overall power consumption of the wireless sensor network system may also increase, which then shorten the lifetime of the system.

In this work, we will demonstrate the seriousness of the pass-over problem through simulation and propose to resolve that by using a variation of the Small-World Routing protocol (SWRP) that we proposed earlier [7]. The SWRP finds paths between the queries and events through recurrent propagations of weak and strong links. Operation of the protocol is simple and does not require much computational power. Yet, with comparable cost and better success rate in route construction, the SWRP protocol is able to find paths for query and event containing less intermediate sensor nodes as compared to the other notable routing protocol, in particular, the rumor routing protocol [8]. According to our simulations, the variation of the SWRP can completely eliminate pass-over occurrence, which contribute to the improvement of success rate in routing and the reduction of average hop count by as much as 30%.

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 of the SWRP and how it can be modified for use in resolving the pass-over problem will be given in Section III. Simulation results showing the effectiveness of the proposed method will be described in Section IV. Finally, we will conclude this paper and list possible future research directions in Section V.

II. RELATED WORK

Flooding [9] 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 [8]. 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 [10]. 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) [11] 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 [12] 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 require 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 [13]. 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.

All of the above mentioned protocols either focus on preserving energy or looking for a shorter path. Unfortunately, none of them address the pass-over issue.

III. THE SWRP PROTOCOL AND ITS VARIATION

In this section, we first briefly describes the SWRP protocol, follows by proposing a variation of the SWRP aims at solving the pass-over problem.

A. The SWRP

The term small world network, was first mentioned by Watts and Strogatz [14] 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 [15]). The key lies in the use of weak links, with which people can often relate themselves to ones that are distant away.

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) [7].

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.

Figure 2 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 (represents in solid lines) and 1 weak link (represents 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.

**B. Variation of SWRP for the pass-over problem**

As we can see, the operation of the SWRP protocol is characterized by four parameters, namely, α, β, γ and H. Any change to one of the four parameters may potential change the route searching procedure, which makes SWRP a very flexible routing protocol.

However, 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. It has been shown the total number of broadcasts can be represented as follows [7]:

$$N_f = \frac{(β \cdot γ) [(α + β)^n - 1]}{(α + β - 1)}$$

(1)

It appears that the number of broadcasts can be substantial as H increases and (α+β) increases. To reduce the number of growing branches (and thus the number of broadcasts), we can revise the operation of the SWRP so that the agent propagates along the search path in a more conservative and (hopefully) effective way. For example, we can constrain the expansion of strong links by limiting their branching 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. Figure 3 shows an example (with α=3 and β=1) illustrating this revision. 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 may be constrained to one after the first phase of expansion.

![Fig. 3. An example of one possible variation of the SWRP with α=3 and β=1 (note that the strong links only branch in the first phase).](image)

Note that the above SWRP variations are just two of many potential possibilities of the SWRP protocol. In fact, the notable rumor routing is also a special case of SWRP with α=0, γ=1 and β being the number of agents. For convenience, we will refer rumor routing with β agents as RRβ.

To reduce the chance of pass-over, we can revise RRβ by expanding the coverage area of query line and/or event line with one-hop broadcast. To be more specific, in the case of RR1, we can achieve this goal by setting α=∞ and limiting the expansion of strong links to only once in each search forwarding step. In practice, α can not equal ∞, it may merely indicate there are strong links from the originating node to all the neighboring nodes that are within its communication range. An example of RR1 with query line expanding its coverage to the one-hop neighbors, referred to as RR1Q, is depicted in Figure 4. Note, the expansion of strong links can be occurring on the event line,
too. In that case, it is represented by RR1E. Accordingly, RR1QE then denotes both the query and event line expand the strong links to the one-hop neighbors throughout the search forwarding process.

![Fig. 4. A possible variation of SWRP for elimination of the pass-over problem (with $\alpha=\infty$, $\gamma=1$, $\beta=1$, and limit the expansion of strong links to only once in each search forwarding step).]

**IV. SIMULATION RESULTS**

We have designed and conducted a number of simulations to explore whether this variation of SWRP protocol can eliminate the pass-over occurrence and to evaluate how it affects the routing performance. 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. Protocols such as RR1, RR2 and their corresponding SWRP variations (RR1Q, RR1E, RR1QE and RR2QE) are investigated. The number of average pass-over occurrence is recorded in addition to two other performance metrics: (1) success rate in finding a path between the event and query and (2) the average number of hop counts of the routing path. The above three metrics with various protocols are compared as functions of the number of broadcasts. Simulation results, as shown in Figure 5-7 and Table 1, represent averages of 200 test sample runs, with both the event and query nodes selected randomly in each run.

First of all, it is apparent that all variations of SWRP under investigation can effectively eliminate the occurrence of pass-over according to Figure 5 (number of pass-over equals 0 for RR1Q, RR1E, RR1QE and RR2QE). The cut-down on pass-over does have positive effect on the success rate and average hop count according to Figure 6 and 7. In addition, a few more observations are summarized as follows: (1) the improvement of the both metrics are greater when expanding the strong links on both the query and event lines; (2) effect on expanding the strong links on either query or event line is virtually the same; (3) the reduction on the average hop count increases when more agents (RR2QE) are involved. However, increase in number of agents may also hurt a little on success rate in case the total number of broadcast is limited to 400 and below. In other words, as broadcasts go beyond 400, success rate of RR2QE (and all other variations of SWRP) reaches 100% with the average hop count substantially lower (approximately 12 to 21 less).

Second, we would like to further explore the impact of the pass-over problem. Let us focus only on RR1 and RR1QE as shown in Table 1. As we can see, there is about one pass-over occurrence for RR1 and zero for RR1QE when the number of broadcast equals 122. However, the difference in success rate and average hop count are 10% (81% for RR1 and 91% for RR1QE) and 3.34 (33.59 for RR1 and 30.25 for RR1QE). To be more specific, a merely one occurrence of pass-over may potentially cause a 10% drop in success rate and more than 3 additional hops to go between the query and event nodes. When the number of broadcast reaches 282, the difference in pass-over occurrence for RR1 is roughly 3. In this case, the success rate for both RR1 and RR1QE have reached stabilizing 100%. However, the query and event nodes may in average go through 15.48 hops more with RR1 than its RR1QE counterpart.
to only once in each search forwarding step, we are able to
\[ H = 1, \] varying \( \alpha, \beta, \gamma \) and \( \delta \). It can be seen the SWRP

\[ \text{Table 1. Effect of pass-over occurrence on the success-rate and average hop count.} \]

<table>
<thead>
<tr>
<th>protocol</th>
<th>metric</th>
<th># of pass-over</th>
<th>success rate</th>
<th>average # of hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR1 (122(^a))</td>
<td></td>
<td>0.93</td>
<td>81%</td>
<td>33.59</td>
</tr>
<tr>
<td>RR1Q (122(^a))</td>
<td></td>
<td>3.05</td>
<td>100%</td>
<td>30.25</td>
</tr>
<tr>
<td>RR2 (282(^a))</td>
<td></td>
<td>0</td>
<td>91%</td>
<td>38.96</td>
</tr>
<tr>
<td>RR2QE (282(^a))</td>
<td></td>
<td>0</td>
<td>100%</td>
<td>44.44</td>
</tr>
</tbody>
</table>

\(^a\) The number in parentheses represents the number of broadcasts.

Finally, we need to point out that an increase in hop count not only lengthen the communication delay, but also have a negative impact on power consumption (and thus the lifetime) of nodes within the wireless sensor network. Accordingly, the variations of SWRP that are introduced in this paper should be able to increase the lifetime of wireless sensor networks as compared to the rumor routing protocol. Furthermore, depending on the requirements of a wireless sensor network, different variation of SWRP can be applied. For example, in case high success rate with less broadcasts is the primary goal, RR1QE may be used. On the other hand, when lower hop count is essential and a little higher broadcasts can be tolerated, then RR2QE may be the one of choice.

V. SUMMARY AND FUTURE RESEARCHES

In this paper, we modify the small-world routing protocol to tackle the pass-over problem in wireless sensor networks. The operation of the SWRP protocol is characterized by four parameters, namely, \( \alpha, \beta, \gamma \) and \( \delta \). It can be seen the SWRP protocol is very flexible as any change to one of the four parameters may potential change the route searching procedure. With \( \gamma = 1 \), varying \( \delta \) and \( \beta \) being the number of agents, together with setting \( \alpha = \infty \) and limiting the expansion of strong links (\( \alpha \)) to only once in each search forwarding step, we are able to derive a variation of the SWRP specifically for the pass-over problem. The simulations results shown in this paper demonstrate that the pass-over problem can be completely eliminated. As a result of that, the average hop counts between the query and event is reduced substantially and the success rate is also improved too.

In the future, we will continue to investigate the effect of cross-over on the power consumption and overall lifetime of a wireless sensor network.

REFERENCES