

# Spatial-Temporal Relation-Based Energy-Efficient Reliable Routing Protocol in Wireless Sensor Networks

**Min Chen**

Department of Electrical and Computer Engineering  
University of British Columbia, Vancouver V6T 1Z4, Canada  
Email: minchen@ece.ubc.ca

**Taekyoung Kwon\***

School of Computer Science and Engineering  
Seoul National University, Seoul, 151-744, Korea  
Email: tkkwon@snu.ac.kr

\*Corresponding author

**Shiwen Mao**

Department of Electrical and Computer Engineering  
Auburn University, 200 Broun Hall, Auburn, AL 36849-5201, USA  
Email: smao@ieee.org

**Victor C.M. Leung**

Department of Electrical and Computer Engineering  
University of British Columbia, Vancouver V6T 1Z4, Canada  
Email: vleung@ece.ubc.ca

**Abstract:** Delivering sensory data to the sink reliably in wireless sensor networks (WSNs) calls for a scalable, energy-efficient, and error-resilient routing solution. In this paper, a Spatial-Temporal relation-based Energy-Efficient Reliable (STEER) routing protocol is proposed to achieve the above goals for WSNs. As opposed to the next-hop-selection-first, data-relay-next approach, which is typical in traditional routing protocols in WSNs, STEER reverses these two steps. In unreliable communication environments, traditional sensor routing protocols may fail to deliver data in a timely manner since a link/node failure can be found out only after multiple unsuccessful retransmissions in the MAC layer, which then sends a failure notification back to the network layer for selecting an alternate next hop. In STEER, each data packet is relayed by broadcasting, and, among the neighbors (closer to the sink) that receive the data, one next-hop node will be elected. In so doing, eligibility as a next hop is evaluated by *temporal gradient*, which is similar to backoff for channel access in IEEE 802.11 systems. The value of *temporal gradient* is determined by the spatial information of each neighbor, i.e., its proximity to the sink. To quantify the *temporal gradient* systematically, a *spatial-temporal mapping function* is proposed in this paper. Comprehensive simulations show that STEER performs well to provide efficient and robust routing in highly unreliable WSNs.

**Keywords:** Energy efficient; multipath routing; reliability; wireless sensor networks.

**Biographical notes:** Min Chen was born on Dec. 1980. He received BS, MS and Ph.D degree from Dept. of Electronic Engineering, South China University of Technology, in 1999, 2001 and 2004, respectively. He is a postdoctoral fellow in Communications Group, Dept. of Electrical and Computer Engineering, University of British Columbia since Mar. 2006. He was a post-doctoral researcher in Multimedia & Mobile Communications Lab., School of Computer Science and Engineering, Seoul National University in 2004 and 2005. His current research interests include wireless sensor network, wireless ad hoc network, and video transmission over wireless networks.

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## 1 INTRODUCTION

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Recent years have witnessed a growing interest in deploying large populations of micro-sensors that collaborate in a distributed manner to gather and process sensory data and deliver them to a sink node by wireless communications. Sensors are expected to be inexpensive and can be deployed in a large number to work in harsh environments, which implies that sensors are typically operating unattended. Also, wireless sensor networks (WSNs) are subject to high fault rates, as connectivity between nodes can be lost due to noise, interference and obstacles that degrade signal reception, and nodes may die due to battery depletion, environmental changes or malicious destruction. In such an environment, reliable data delivery over error-prone wireless channels is particularly challenging, as potential solutions also need to be energy-efficient to prolong the lives of sensor nodes operating with limited battery power. In addition, some WSN applications also require timely data delivery. For example, when a target enters an area of interest, it may be critical to reduce the delay of sensor reports. If the reported event is not received by the sink node within a certain deadline, reported information may be obsolete and useless.

These characteristics of WSNs make the design of routing protocols challenging. To address such challenges, many studies have focussed on a subset of the following requirements: prolonging the network lifetime by exploiting energy efficiency, supporting reliability, fast delivery of delay-sensitive data, and achieving low-cost sensor design. However, the unreliable, mobile, and large-scale environments Present many conflicting requirements as discussed below.

- *Reliability vs. low-cost sensor design:* In order to recover packet losses, hop-by-hop based reliable communication protocols such as PSFQ (C. Wan et al., 2005) and RMST (F. Stann et al., 2003) are proposed, since end-to-end recovery is not adequate nor energy efficient to achieve reliability. However, hop-by-hop recovery techniques require sensor nodes to have a high memory capacity for error control, which increases the hardware complexity of sensor nodes.
- *Reliability vs. energy efficiency:* Many multipath routing schemes, which set up multiple paths to increase reliability, fall into this category. However, the associated multipath routing overhead may be too high for dense, large scale WSNs. In general, the energy efficiency objective and the reliability objective conflict with each other. Thus, most of the previous reliable routing schemes aim to satisfy the required reliability by tuning the redundancy level to minimize energy consumption, such as adjusting the number of paths (D. Ganesan et al., 2002), the number of data copies delivered to the next hop (B. Deb et al., 2003), the “width” of the forwarding mesh (F. Ye et al., 2005), or the reporting rate of sensor nodes (Y. San. et al., 2003).

- *Energy efficiency vs. timely delivery:* Timely delivery of data is required in many applications of WSNs, such as real-time target tracking in battle environments, emergent event triggering in monitoring applications, etc. K. Akkaya et al. (2004) proposed an energy-aware QoS routing protocol to maximize the throughput of the best-effort traffic while meeting the end-to-end delay constraint of the real-time traffic. Similarly, EDDD (M. Chen et al., 2006) globally balances the energy consumption for best-effort traffic to prolong network lifetime while providing service differentiation for time-sensitive traffic to lower the end-to-end delay.

Traditional routing protocols for ad hoc and sensor networks usually operate in two steps as follows: 1) the next hop node(s) are selected first; 2) packets are forwarded to the selected node(s). We call such an approach “transmitter-oriented” in this paper. In step 1, the current node must acquire its neighbor information. This is usually done by exchanging control messages between neighbors, typically in a periodic manner. In position-based schemes, the positions of a node’s neighbors are obtained through beaconing. Having the neighbor information, special metrics are used to evaluate each neighbor, and the best neighbor will be selected as the next hop. For example, directed diffusion (DD) (C. Intanagonwivat et al., 2000) proposes the use of “gradient” to evaluate the eligibility of a neighbor node as the next-hop node for data dissemination; in GPSR (B. Karp et al., 2000), packets are forwarded to the node that makes the most progress towards the sink. In step 2, data caching and retransmission can be exploited to provide reliability by trading off energy efficiency or delay.

In a reliable networking environment, link/node failures seldom happen. Thus, the network can afford the relatively expensive link repairs by flooding control packets. However, WSNs are more prone to link/node failures than ad hoc networks and wireless LANs. Hence, such traditional routing protocols become less effective. The above step 1 may operate blindly since the current node does not know whether or not the selected “next hop” is alive until retransmitting the packet for a pre-determined number of times. In case of link/node failures, therefore, energy will be wasted, and delivery latency will be increased. Such a “transmitter-oriented” approach is not suitable to achieve the goals of high reliability and energy efficiency, timely delivery, and low-cost sensor design simultaneously in unreliable environments.

The main contribution of this paper is proposing a “receiver-oriented” Spatial-Temporal relation-based Energy-Efficient Reliable routing protocol (STEER) for WSNs. In traditional approaches, a path is first established before data transmission. In a highly dynamic environment, the problem is that the path (or links, or next hop nodes) chosen at an earlier time may not work well during data transmissions after a while. In this paper, we present a novel receiver-driven approach, where a packet is broadcast first, and the node closest to the sink among those neighbors that receive the packet will be chosen as

the next hop relay in a distributed manner. We also adopt a spatial temporal mapping to shorten the delay of the next hop node selection. STEER only uses local information and hence it is scalable. Its complexity is only a function of the number of neighbors (or node density), which does not generally increase with the network scale or the total number of nodes.

The rest of this paper is organized as follows. Section 2 presents the related work. We discuss the design issues addressed by STEER in Section 3, and describe the STEER algorithm in Section 4. Simulation model and results are presented in Sections 5 and 6, respectively. Section 7 concludes the paper.

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## 2 Related Work

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Our work is close to that of M. Zorzi et al. (2003) and the more recent work by S. Biswas et al. (2005), in which efficient methods of using multi-receiver diversity for packet forwarding are explored. Our work is also closely related to the reliable data transfer scheme or geographic routing in WSNs. We will give a brief review of the work in these two aspects.

There are increasing research efforts on studying the issue of reliable data transfer in WSNs (C. Wan et al., 2005; F. Stann et al., 2003; Y. San. et al., 2003; D. Ganesan et al., 2002; B. Deb et al., 2003; F. Ye et al., 2005). In these studies, hop-by-hop recovery (C. Wan et al., 2005; F. Stann et al., 2003), end-to-end recovery (Y. San. et al., 2003), and multi-path forwarding (D. Ganesan et al. (2002); B. Deb et al. (2003); F. Ye et al. (2005)) are the major approaches to achieve the desired reliability. PSFQ (C. Wan et al., 2005) works by distributing data from source nodes in a relatively slow pace and allowing nodes experiencing data losses to recover any missing segments from immediate neighbors aggressively. PSFQ employs hop-by-hop recovery instead of end-to-end recovery. In F. Stann et al. (2003), the authors proposed RMST, a transport protocol that provides guaranteed delivery for application requirements. RMST is a selective NACK-based protocol that can be configured for in-network caching and repair. In D. Ganesan et al. (2002), multiple disjoint paths are set up first, then multiple data copies are delivered using these paths. In B. Deb et al. (2003), a protocol called ReInForM is proposed to deliver packets at a desired level of reliability by sending multiple copies of each packet along multiple paths from sources to sink. The number of data copies (or, the number of paths used) is dynamically determined depending on the probability of channel error. Instead of using disjoint paths, GRAB (F. Ye et al., 2005) uses a path interleaving technique to achieve high reliability. It assigns the amount of credit  $\alpha$  to each packet at the source.  $\alpha$  determines the “width” of the forwarding mesh and should be large enough to ensure robustness but not to cause excessive energy consumption. It is worth noting that although GRAB (F. Ye et al., 2005) also exploits data broadcasting to attain high reliability, it may not be energy-efficient

because it may involve many next-hop nodes in order to achieve good reliability and an unnecessarily large number of packets may be broadcast. By comparison, in STEER a data packet is only broadcast once per hop, and it is quite robust to link/node failures. Some researchers explore the special features of sensor applications in reliable protocol design. For example, considering the asymmetric many-to-one communication pattern from sources to sink in some sensor applications, data packets collected for a single event exhibit high redundancy. Thus, some reliable techniques (C. Wan et al., 2005; F. Stann et al., 2003) proposed for WSN would either be unnecessary or spend too much resources on guaranteeing 100% reliable delivery of data packets. Exploiting the fact that the redundancy in sensed data collected by closely deployed sensor nodes can mitigate channel errors and node failures, ESRT (Y. San. et al., 2003) intends to minimize the total energy consumption while guaranteeing the end-to-sink reliability. In ESRT, the sink adaptively achieves the expected event reliability by controlling the reporting frequency of the source nodes. However, in the case that many sources are involved in reporting data simultaneously to ensure some reliability (e.g., in a highly unreliable environment), the large amount of communications are likely to cause congestion.

Geographic routing is a routing method where the locations of the network nodes are used for packet forwarding. In most position-based routing schemes, the minimum information a node must have to make useful routing decisions is its position (provided by GPS, Galileo, etc.), the position of its neighbors (obtained through beaconing), and the final destination’s location (obtained through a so-called location service (J. Li et al., 2000)). The most popular forwarding method in this category is greedy forwarding, where forwarding decisions are made locally based on information about their one-hop neighborhood (B. Karp et al., 2000; Y. Yu et al., 2001). To route around areas where greedy forwarding cannot be used, Greedy Perimeter State Routing (GPSR) (B. Karp et al., 2000) tries to find the perimeter of the area. Packets are then routed along this perimeter, around the area.

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## 3 Overview of the STEER Design

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In this section, we discuss the key design features of STEER to address the challenges mentioned in Section 1.

### 3.1 Energy efficiency

First, the intermediate nodes only need to maintain the identifier of its next hop in STEER. The control overhead of setting up neighbor information by message flooding or beaconing is saved. Second, in an unreliable environment, it would be desirable for a sensor not to waste its energy by unnecessary data transmissions. In other words, the sensor should minimize the number of retransmitted data packets.

### 3.2 Reliability

STEER selects the next hop of a packet’s route after the packet transmission. Source as well as intermediate nodes broadcast packets without specifying the next hop nodes. The responsibility for choosing the next hop is shifted to the set of nodes that successfully receive a specific packet broadcast. If there are no such available neighbors, STEER will address the resulting dead end problem L. Zou et al. (2005).

### 3.3 Low-Cost Sensor Design

Traditional sensor routing protocols usually require a sensor node to maintain the information of multiple routes and/or neighbors. In a very large scale network, the amount of the routing information and neighbor information may pose an additional challenge for the sensors with low storage capacity. With STEER, a sensor node only need to record the identifier of its next hop node.

Moreover, data caching is an important technique to recover packet loss due to route breakdowns (A. Valera et al., 2005). However, additional storage overhead is required for data caching, which conflicts with the design goal of memory-constrained sensors. Also, data caching in unreliable environments also incurs queuing delays. For example, in unreliable environments, bursty packet arrivals are likely to cause congestion in the cache buffers. Thus, the end-to-end delays of these packets increase. In STEER, data caching only happens in the next hop choosing phase. Once the next hop is selected, all the nodes caching the data will clear their memories immediately.

### 3.4 Fast Delivery

In STEER, the data packet delay at each hop consists of two parts: (1) the delay for choosing the next hop; (2) the delay for a single data transmission. The first delay element can be reduced by tuning the criteria of selecting next hop. To achieve fast data delivery, STEER should shorten the next-hop-selection delay as much as possible. A suitable algorithm will be found to achieve this goal.

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## 4 The STEER Algorithm

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In Section 4.1, we describe the basic STEER protocol. Then, in Section 4.2, the route selection process of STEER is introduced. In Section 4.3, a Spatial-temporal Mapping Function (STMF) is introduced to achieve fast data delivery.

### 4.1 The Basic STEER Protocol

In STEER, each node has a “flow-entry” that indicates the identifier of its next hop node for forwarding data to the sink. The flow-entries of all the sensor nodes are empty at first.

We denote a transmitter (the source or an intermediate node) by “ $h$ ”. The arrival of a sensory data packet (from the application layer of the source node or from the upstream node) triggers  $h$  to check its flow-entry. Since the flow-entry does not exist initially,  $h$  stores the data, starts a “route selection” process immediately to set up the flow-entry, and then transmits the stored data to the selected next hop node  $i$ . If  $h$  fails to deliver a data packet to  $i$ ,  $h$  will initiate route reselection. In addition, route selection/reselection (denoted by Sel/Resel, respectively) itself may fail. In this case, node  $h$  unicasts a next-hop-reselection message (RESEL) to its previous hop node which will trigger a new route reselection, and so forth. Any node who finds itself a dead end will keep silent so that it won’t be selected by the transmitter, until it has available neighbors again. The flowchart of the basic STEER Protocol is shown in Fig. 1.

### 4.2 The Route Selection/Reselection Mechanism

To initiate route Sel/Resel, a node (e.g., node  $h$ ) broadcasts a probe message (PROB) at first. Its neighbors, which receive this PROB and are closer to the sink than node  $h$ , are called “live candidates ( $LC$ s)”. An  $LC$  will calculate its Temporal Gradient ( $TG$ ), as specified in Section 4.3.2. Then the  $LC$  sets its “ $TG$ -Timer” to the computed  $TG$  value.

Since multiple  $LC$ s likely starts their  $TG$ -Timers simultaneously, the one with the least  $TG$  will expire first and becomes a “reserved next hop” (RNH), which is highly likely to be selected as the next hop node later.

Ideally, all the  $LC$ s except the RNH should cancel their  $TG$ -Timers and delete the packet from their forwarding buffers when the RNH’s  $TG$ -Timer expires. To achieve this, STEER operates as follows:

1. RNH broadcasts a “reply” message (REP) to node  $h$ ;
2. If node  $h$  receives the REP from RNH, it will broadcast a “selection” message (SEL) with the identifier of the RNH, and start the selection-retransmission-timer (SEL-ReTx-Timer). To guarantee that only one  $LC$  be selected as the next hop node, node  $h$  only accepts the first REP sent by the RNH while ignoring the later ones. Note that the  $LC$ s overhearing the REP will back out (i.e., cancel their  $TG$ -Timers and delete the buffered packet) instantly;
3. If the RNH receives the SEL, it becomes the next hop node and relays the data by broadcasting. When other  $LC$ s receive the SEL, they will cancel their  $TG$ -Timers and drop the PROB message;
4. If node  $h$  receives the broadcast PROB from its next hop node (the above RNH), it will cancel its SEL-ReTx-Timer. Otherwise, it will re-broadcast the SEL when the SEL-ReTx-Timer expires, and will start the timer again until the retry limit is reached.

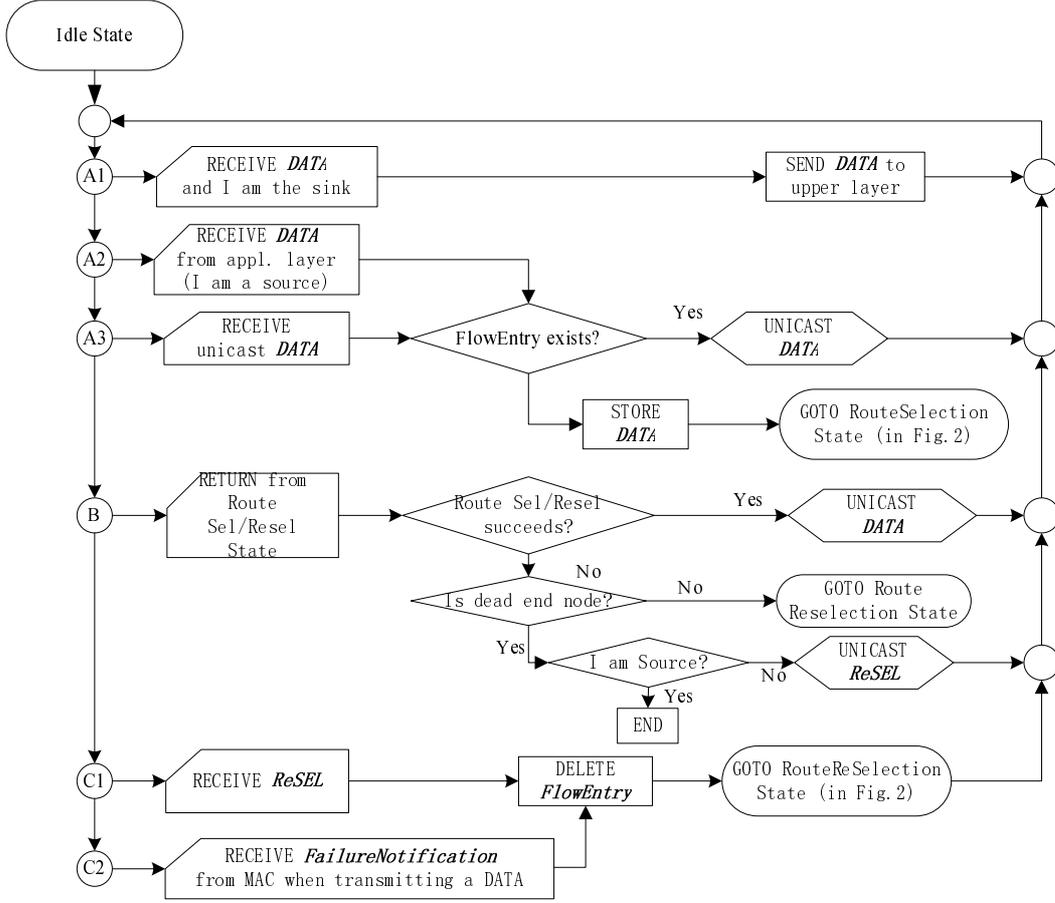


Figure 1: Flowchart of the Basic STEER Protocol.

5. If the RNH receives re-transmitted SEL, it will “unicast” an “selection-reply” message (SEL\_REP) to node  $h$ ;
6. If node  $h$  receives SEL\_REP, it will cancel its SEL-ReTx-Timer.

Note that in step (1) two (or more) LCs with similar TGs broadcast their REPs simultaneously. If collision happens, both of the LCs will not be selected, and other LCs broadcast REPs later when their TG-Timers expire will be selected.

Furthermore, in the above step (2) it is possible that the SEL may collide with a new REP from other LC, which would cause the following two disadvantages: (a) RNH may fail to receive the SEL; (b) other LCs (non-RNH nodes) do not delete the data from their caches at the earliest opportunity. Case (b) only increases data caching time and control overhead, while case (a) will cause the failure rate of the current data delivery if left without any countermeasure. To ensure that the RNH receives the SEL at least once, node  $h$  should send the SEL again when SEL-ReTx-Timer expires.

The flowchart of the route Sel/Resel of the RLRR Protocol is shown in Fig. 2, where the *NoREP-Timer* is used to decide a transmitter is a dead end node if it does not receive any REPs until the *NoREP-Timer* expires.

### 4.3 Spatial-Temporal Mapping

In Section 4.3.1, we firstly present how an LC gets its relative coordinates. Then, based on the relative coordinates, an optimal spatial-temporal mapping function (STMF) is defined in Section 4.3.2.

#### 4.3.1 Obtaining Neighborhood Spatial Information

In most position-based routing approaches, the minimum information a node must have in order to make useful routing decisions is its own position, the positions of its neighbors (through beaconing), and the sink’s location. The absolute geographical location is obtained by means of GPS. We assume that each node knows its own geographic position. In the global coordinate system ( $o$  is the origin) of Fig. 3, we assume that LC  $i$  knows its position  $(x_i^o, y_i^o)$ , the position  $(x_h^o, y_h^o)$  of its previous hop  $h$ , which is piggybacked in the PROB message, and the sink’s location  $(x_t^o, y_t^o)$ . To obtain the neighborhood spatial information, we build a relative two-dimensional coordinate system where  $h$  is the origin, and the  $X$ -axis is the line between node  $h$  and the sink. The relative coordinates  $(x_i, y_i)$  of  $i$  can be calculated by Eqn.(1).



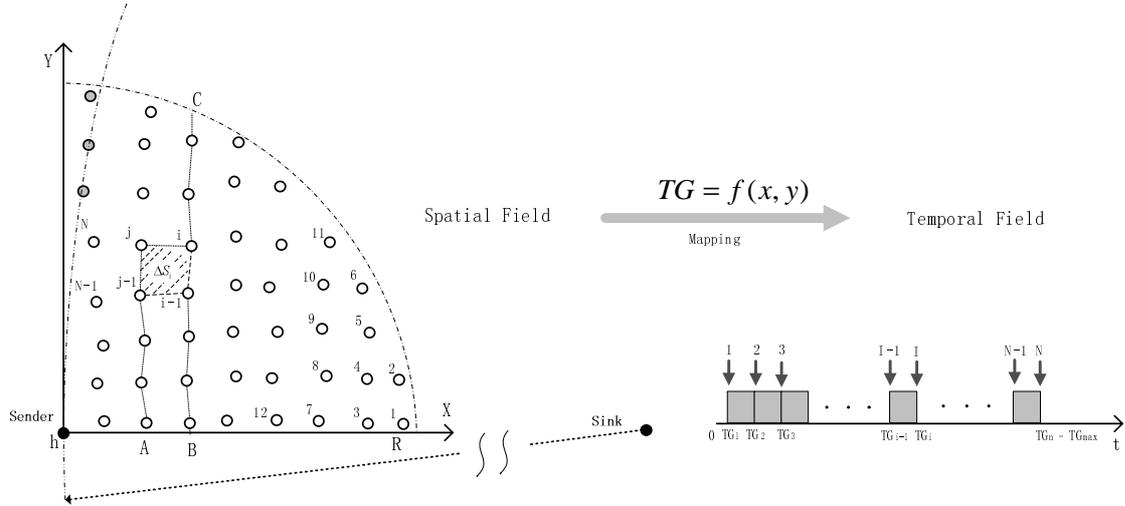


Figure 4: Mapping Neighborhood Spatial Information to Temporal Information using STMF.

In Fig. 4, node  $i-1$  and  $i$  are two nodes with successive TGs. (e.g.  $TG_{i-1}$  and  $TG_i$  in the right side of Fig. 4. We define the gap of the two TGs with successive eligibility orders as follows:

$$\Delta TG_i = TG_i - TG_{i-1} = f(x_i, y_i) - f(x_{i-1}, y_{i-1}). \quad (3)$$

$\Delta TG_i$  is deemed as the granularity of TG. Here,  $\Delta TG_i$  should be large enough to differentiate two nodes with successive TGs, and as small as possible to obtain a low next-hop-selection delay. At its minimum,  $\Delta TG_i$  could be set as the time duration to transmit a control message (i.e., REP message in Section 4.2) in the MAC layer. In this paper, we use  $T_{REP}$  to denote the lower bound of  $\Delta TG_i$ . Thus, a suitable STMF should make  $\Delta TG_i$  close to  $T_{REP}$ , as formulated in Eqn.(4) where  $\epsilon$  is a small positive constant.

$$\Delta TG_i \rightarrow T_{REP} + \epsilon, \quad \forall i = 1, 2, \dots, N. \quad (4)$$

In Fig. 4, we can divide the forwarding region into  $N$  sections, each occupied by a single node. Then let  $\Delta S_i$  be the size of the area that node  $i$  occupies. Assume a certain topology monitoring algorithm (B. Chen et al., 2001; C. Schurgers et al., 2002) is adopted to keep a certain node density by adjusting sleep duty cycle in a dense sensor network. Thus, LCs can be deemed nearly uniformly distributed, and we have

$$\Delta S_i \rightarrow \Delta S = \frac{A}{N}. \quad (5)$$

In Eqn.(5),  $A$  is the size of the area which covers the LCs (e.g.,  $A \approx \pi R^2/4$  in Fig. 4). Let  $T_{REP} + \epsilon = \alpha \cdot \Delta S$ , so that  $\alpha = \frac{T_{REP} + \epsilon}{\Delta S} \approx \frac{T_{REP} \cdot N}{A}$ . Then,

$$\alpha \Delta S_i \rightarrow T_{REP} + \epsilon. \quad (6)$$

In order to satisfy Eqn.(4), we can set  $\Delta TG_i$  to  $\alpha \Delta S_i$ .

Thus, the STMF is obtained as follows:

$$\begin{aligned} f(x_i, y_i) &= \sum_{k=1}^i \Delta TG_k = \sum_{k=1}^i \alpha \cdot \Delta S_k \\ &\approx \alpha \cdot (S_{AjiB} + S_{BCR}) \\ &\approx \frac{T_{REP} \cdot N}{A} \left( \sqrt{\frac{A}{N}} \cdot y + \int_x^R \sqrt{R^2 - x^2} dx \right) \\ &= \frac{TG_{max}}{A} \cdot \left( \sqrt{\frac{A}{N}} \cdot y + g(R) - g(x) \right), \end{aligned} \quad (7)$$

where  $g(x) = \frac{x}{2} \sqrt{R^2 - x^2} + \frac{R^2}{2} \arcsin \frac{x}{R}$ . In Eqn.(7),  $R$  denotes the maximum transmission range;  $S_{AjiB}$  denotes the area of rectangle  $A-j-i-B$ ;  $S_{BCR}$  denotes the size of area  $B-C-R$ ;  $TG_{max}$  is a constant that reflects both the granularity of TG and the number of LCs.

Note that the regular grid topology shown in Fig. 4 is for illustration only. The more regular the topology, the more accurate the approximation in Eqn.(6). Actually, STEER does not assume such a regular structure. The approximation error only incurs an increased end-to-end delay. As the adverse situation where there is a void, the update procedure presented in Section 4.2 will work to get around the void.

## 5 The Simulation Model

We implemented a simulation model using OPNET (M. Chen, 2004) to evaluate the performance of STEER and compare with GPSR (B. Karp et al., 2000). The implementation of STEER is limited currently to the basic greedy mode; i.e., all the packets are broadcast and there is no recovery strategy in case no LC exist, and packets are simply dropped. In GPSR, a greedy forwarder will be selected out of the list of neighbors. If the selected neighbor fails to receive a packet, its previous hop node tries to retransmit the packet until the retry limit is reached. Then, a backup node is selected from the neighbor table, and the MAC layer tries to deliver the packet to the this node. If data transmission still fails after trying two backup nodes, we

Table 1: Simulation Setting

Basic Specification	
Network Area	4000m × 1500m
Topology Configuration	Randomized
Total Sensor Node Number	600
Data Rate at MAC layer	2Mbps
Time Duration of State ON	Default: 100s
Node failure rate	Default: 15%
Packet loss rate	Default: 15%
Sensed Traffic Specification	
Size of Sensed Data	Default: 1Kbytes
Sensed Data Packet Interval	1s
STEER Specification	
$TG_{max}$	Default: 25ms
Selection (SEL) message retry limit	2
Waiting time for retransmitting SEL	Default: 8ms

discard the packet. The beacon interval is set to 1 second. We use IEEE 802.11 DCF as the underlying MAC.

We tune the network parameters to get a large-scale sensor network. The network with 600 nodes is three times larger than that used in the original GPSR paper B. Karp et al. (2000). The nodes are randomly placed over a 4000m × 1500m area. The rectangular shape of the simulation area is chosen to obtain longer paths; i.e., a higher average hop count. The sensor node is battery-operated and its transmission range is 250m. The sink node is assumed to have infinite energy supply. It is located close to one corner of the area, while the target sensor nodes are specified at the opposite corner. A source generates one packet per second. We use the energy model presented in M. Chen et al. (2006); L. Feeney et al. (2001); M. Chen et al. (2007a,b).

We employ the link failure model used in M. Chen et al. (2007c). The node failure model is the same as the link failure model. An ON-OFF two state Gilbert-Elliott model (E.O. Elliott et al., 1965) is adopted. State ON represents that the node is in “good” status, while state OFF represents a “node failure” state. Let  $f$  be the node failure rate. With the time duration of state ON ( $T_{on}$ ) fixed, that of state OFF ( $T_{off}$ ) is calculated as a function of  $f$ , i.e.,  $T_{off} = T_{on} \times f / (1 - f)$ . The parameter values used in the simulations are presented in Table 1. The basic settings are common to all the experiments. For each result, we simulate for sixty times with different random seeds and get the average results.

## 6 Performance Evaluation

In this section, four performance metrics are evaluated:

- *Reliability (Packet Delivery Ratio)* - It is the ratio of the number of data packets delivered to the sink to the number of packets generated by the source nodes.
- *Network Energy Consumption* - We use  $e_{steer}$  and  $e_{gpsr}$  to denote the energy consumption in STEER and GPSR, respectively. For both schemes, this includes all the energy consumption of transmitting, receiving, and overhearing.
- *Average End-to-end Packet Delay* - We use  $t_{steer}$  and  $t_{gpsr}$  to respectively denote the end-to-end delay in STEER and GPSR. It includes all possible delays during data dissemination, caused by queuing, retransmission due to collision at the MAC, and transmission time.
- *Energy×Delay/Reliability* - In WSNs, it is important to consider both energy consumption and delay. In S. Lindsey et al. (2002), the combined energy×delay metric is used to reflect both the energy usage and the end-to-end delay. Furthermore, in an unreliable environment, the reliability is also an important metric. In this paper, we adopt the following metric to evaluate the integrated performance of reliability, energy and delay:

$$\frac{energy \cdot delay}{reliability}. \quad (8)$$

### 6.1 Impact of $TG_{max}$ in STEER

In these simulation experiments, we change  $TG_{max}$  from 0.01s to 0.05s with all the other parameters in Table 1 unchanged. Recall that  $TG_{max}$  is a constant that reflects both the granularity of TG and the number of LCs.  $TG_{max}$  has a large impact on the data latency.

Fig. 5 shows that the reliability in STEER grow as  $TG_{max}$  increase. The larger  $TG_{max}$  is, the less is the probability that REPs collide at each hop. Thus, the larger is the success ratio of the data delivery at each hop.

In Fig. 6, when  $TG_{max}$  is small (e.g., 0.01s), many LCs have similar TG values. Thus, they all transmit REPs within a small period, which not only cause a low reliability (none of them is selected as the next-hop node if their REPs collide) but also ineffective use of energy to transmit the REPs. With  $TG_{max}$  increased,  $e_{steer}$  increases because more data packets are delivered successfully to the sink. When  $TG_{max}$  goes beyond 0.03s,  $e_{steer}$  decreases again since collisions rarely happen.

In Fig. 7, when  $TG_{max}$  is small,  $t_{steer}$  is high because of the following two reasons: (i) collisions between REPs transmitted by LCs with similar TGs collide preventing LCs with relatively high eligibility to become a next-hop node; (ii) collisions between SEL messages and new REPs resulting in multiple SEL retransmissions before they are received by the respective RNHs. The figure shows that  $t_{steer}$  decreases as  $TG_{max}$  is increased, and reaches its minimum value when  $TG_{max}$  is equal to 22.5 milliseconds. It is unnecessary to further increase  $TG_{max}$  more if the value is

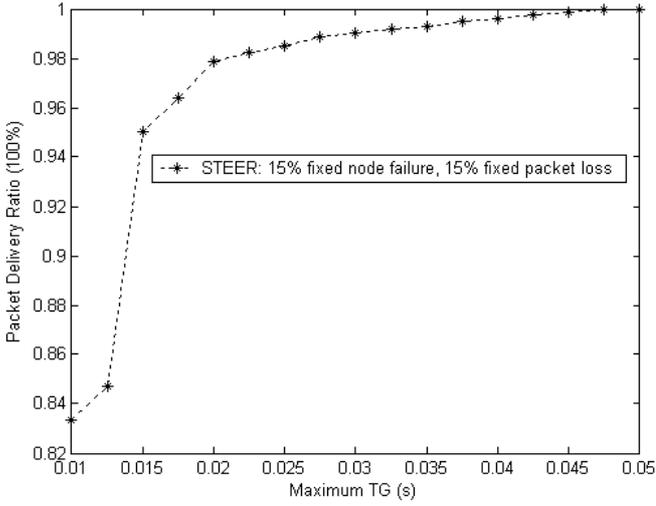


Figure 5: Impact of  $TG_{max}$  on Reliability.

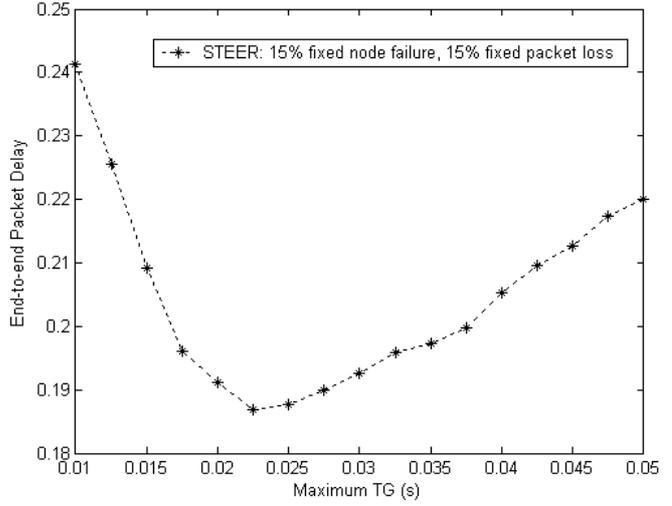


Figure 7: Impact of  $TG_{max}$  on End-to-end Packet Delay.

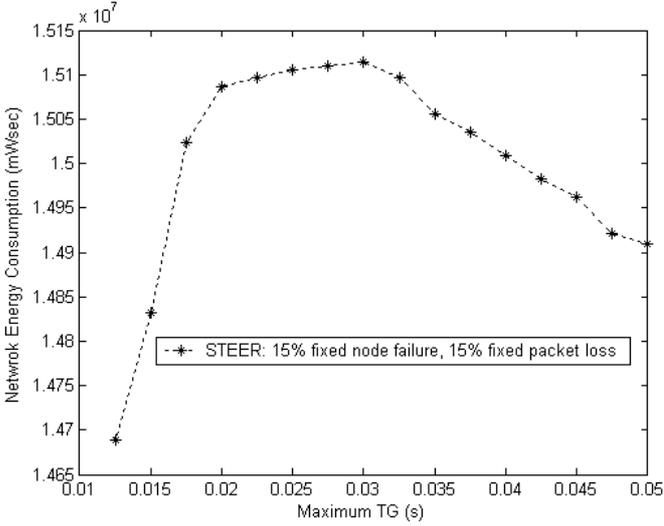


Figure 6: Impact of  $TG_{max}$  on Energy Consumption.

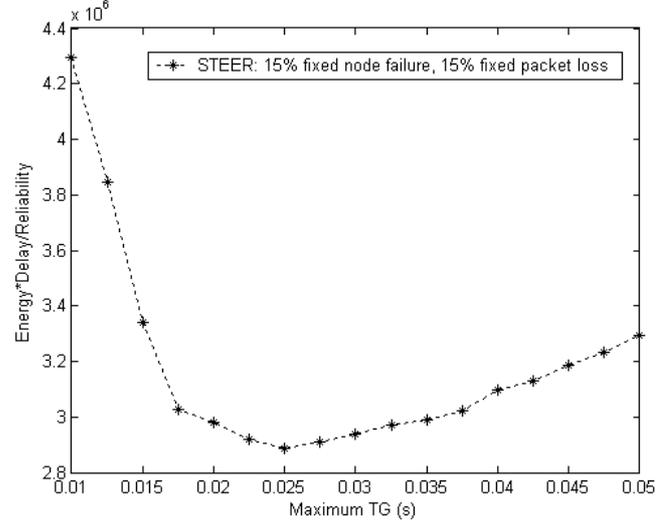


Figure 8: Impact of  $TG_{max}$  on Energy-Delay/Reliability.

large enough to differentiate the  $LCs$ , since a large  $TG_{max}$  also increase the time for next hop selection. Fig. 8 shows that the optimal value  $TG_{max} = 25ms$  gives the best integrated performance.

## 6.2 Performance Comparison of STEER and GPSR

In the implementation of GPSR, packet caching is used to reduce packet loss due to route failures in a WSN. When a node detects a failure in the next hop node or link, it uses an alternative (backup) next hop node. We evaluate the robustness of STEER and GPSR by studying how node failures and packet losses (link failures) affect their reliability in this section. We first vary the node failure rate from 5% to 70%, while using a fixed 15% packet loss rate. Then we vary the packet loss rate from 5% to 70%, while

using a fixed 15% node failure rate. The parameters of both schemes are shown in Table 1.

Fig. 9 shows that the reliability of STEER is better than that of GPSR for most node failure rates and packet loss rates considered. We do not exclude the possibility that providing more backup nodes would yield a better reliability performance for GPSR. However, when the number of backup nodes is increased, the associated routing overhead may become overwhelming, and data latency may increase dramatically. GPSR is more susceptible to node failure than link failure, since its data caching and retransmission become ineffective when node failure rate is high. In contrast, a data packet is always transmitted only once at each hop in STEER. Thus, the reliability performances of STEER is similar for a similar node failure rate and packet loss rate.

Fig. 10 indicates that when the loss rate is relatively low,

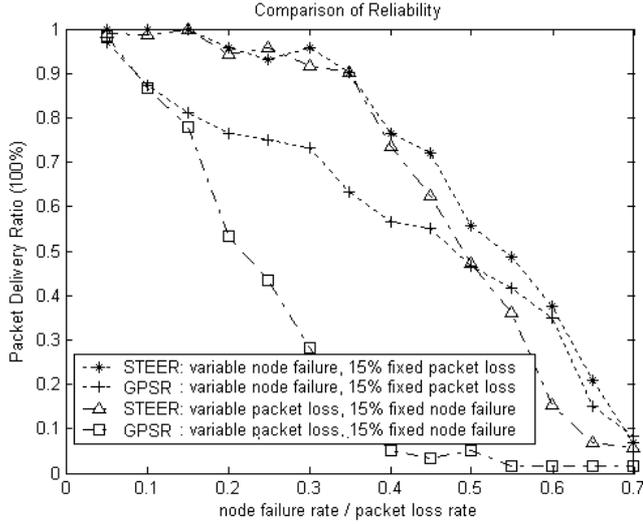


Figure 9: Comparison of Reliability.

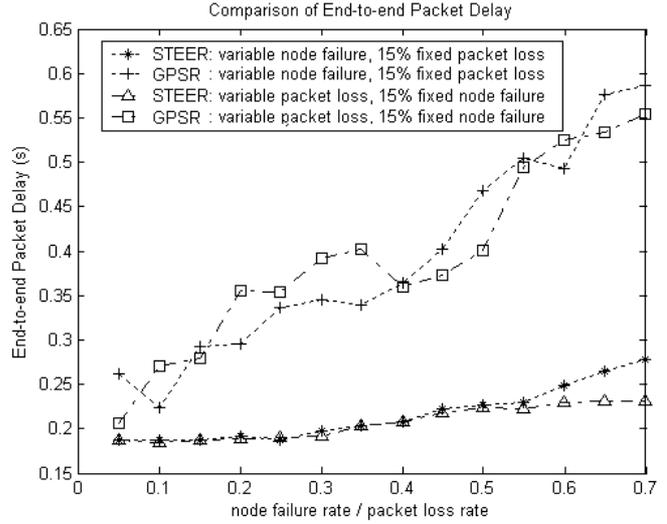


Figure 11: Comparison of End to End Packet Delay.

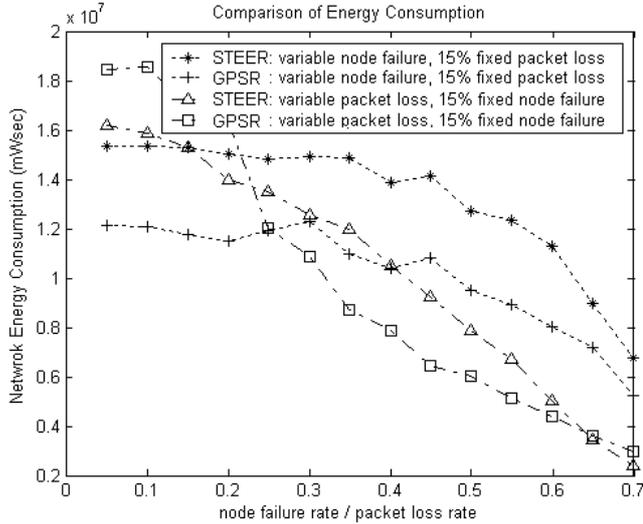


Figure 10: Comparison of Network Energy Consumption.

STEER consumes less energy than GPSR, since no data retransmission is needed to achieve the improvement of reliability. However, with increased loss rates, STEER consumes more energy than GPSR, as increasing node/link failures actually reduce the total energy consumption of GPSR but the reliability become very low. While the results presented in this paper are based on the total energy consumption of the entire WSN, we expect the energy consumption per successful data delivery in STEER is lower than GPSR since more data packets are successfully sent to the sink in STEER. Even though STEER yields similar reliability under a similar node failure rate and packet loss rate, it consumes more energy at a high packet loss rate than at a high node failure rate. The reason is that failed nodes do not continue to consume energy for receiving or overhearing.

In Fig. 11, it can be observed that STEER exhibits much

lower end-to-end delay than GPSR. It shows that STEER not only delivers data in a more timely manner but also shortens the time for data caching. Thus, STEER can reduce the storage requirements for the sensor nodes. Note that the proper selection of an STMF is important as it has a great impact on the delay performance of STEER, as illustrated in Section 6.1. Long delays in GPSR are caused mainly by the link layer retransmissions. When GPSR selects a next hop in its neighbor table and the MAC-layer tries to deliver the packet to this node several times without success due to node/link failure, the MAC-layer sends a failure notification back to the network layer and the routing protocol selects an alternate next hop and repeat the process. When the node or link failure rate is high, the simulations indicate that GPSR has to select several alternate next hop nodes before the MAC-layer is finally able to deliver a packet. The advantage of STEER in terms of end-to-end delay is that its performance is basically independent of whether a failure occur at the next hop node or the link. However, STEER has the disadvantage that it introduces an additional next-hop-selection delay. This drawback vanishes when an optimal STMF is adopted as proposed in this paper.

In Fig. 9, 10 and 11, STEER exhibits more consistent and relatively higher reliability, lower energy-consumption and lower end-to-end packet delay than GPSR in most scenarios. Thus, the  $\frac{\text{Energy-Delay}}{\text{Reliability}}$  of STEER in Fig. 12 is always lower than that of GPSR.

## 7 Conclusions

Traditional routing protocols in WSNs suffer from several drawbacks caused by outdated neighbor tables and control message flooding/beaconing, which degrade network performance. Especially in unreliable environments, an intermediate node does not know that the selected next hop

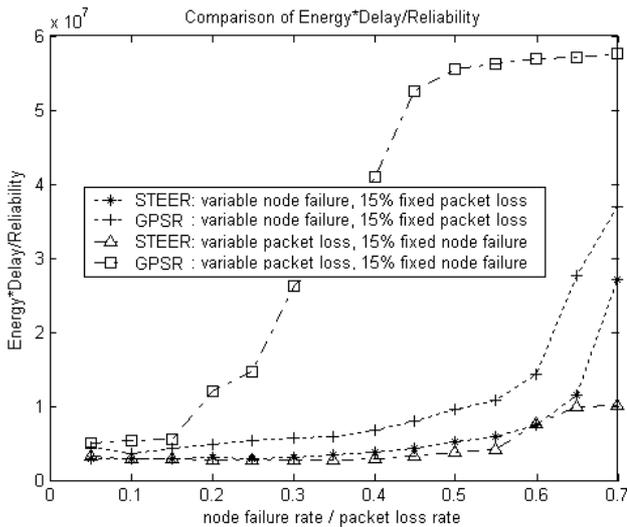


Figure 12: Comparison of Energy·Delay/Reliability.

is dead until it has attempted unsuccessfully to transmit a packet several times to the next hop node. Thus, in case of link/node failures, much energy will be wasted by the unsuccessful data transmissions, and the delivery latency will be increased. We have proposed a novel STEER protocol in this paper, which does not require nodes to have knowledge about their neighborhood. Instead of the next-hop-selection-first, data-relay-next routing procedure followed by most routing protocols, STEER reverses these two steps and adopts a “receiver-oriented” approach. In STEER, broadcast data is received by all the live neighbors with a good link, and the responsibility for choosing the next hop is shifted to these live candidates themselves. Compared with conventional routing protocols, the biggest drawback of STEER is the introduction of next-hop-selection delays. We have solved this problem by finding and exploiting an optimal STMF. Since STEER operates on the actual topology and is completely stateless, the performance is insensitive to whether a failure occur at a node or link. Extensive simulations have been carried out to show that STEER exhibits more consistent and relatively higher reliability, lower energy-consumption and lower end-to-end packet delay than GPSR. The overall performance gain of STEER over GPSR increases as the node/link failure rate increases.

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## REFERENCES

- M. Zorzi and R. Rao, (2003) ‘Geographic Random Forwarding (GeRaf) for ad hoc and sensor networks: multihop performance’, *IEEE Transactions on Mobile Computing*, Oct., Vol.2, No. 4, pp.337-348.
- S. Biswas and R. Morris, (2005) ‘ExOR: Opportunistic Multi-Hop Routing for Wireless Networks’, *ACM Sigcomm’05*, pp.133-144.
- C. Wan, A. Campbell, and L. Krishnamurthy, (2005) ‘Pump-Slowly, Fetch-Quickly (PSFQ): A Reliable Transport Protocol for Sensor Networks’, *IEEE Journal of Selected Areas in Communications*, April, vol.23, pp.862-872.
- F. Stann and J. Heidemann, (2003) ‘RMST: reliable data transport in sensor networks’, in *Proceedings of the IEEE International Workshop on Sensor Network Protocols and Applications*, May, pp.102-112.
- D. Ganesan, R. Govindan, S. Shenker and D. Estrin, (2002) ‘Highly Resilient, Energy Efficient Multipath Routing in Wireless Sensor Networks’, In *Mobile Computing and Communications Review (MC2R)*, vol 1., no. 2, pp. 10-24.
- B. Deb, S. Bhatnagar and B. Nath, (2003) ‘ReInForM: reliable information forwarding using multiple paths in sensor networks’, *IEEE LCN*, Oct., pp.406-415.
- F. Ye, G. Zhong, S. Lu, and L. Zhang, (2005) ‘GRAdient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks’, *ACM Wireless Networks*, Vol.11, No.3, pp.285-298.
- Y. Sankarasubramaniam, O. Akan and I. Akyildiz, (2003) ‘ESRT: Event-to- Sink Reliable Transport in Wireless Sensor Networks’, *Proc. of ACM MobiHoc’03*, June, pp.177-188.
- B. Karp and H.T. Kung, (2000) ‘GPSR: Greedy perimeter stateless routing for wireless networks’, *Proc. of ACM MobiCom’00*, August, pp.243-254.
- Y. Yu, R. Govindan and D. Estrin, (2001) ‘Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks’, *UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023*, May.
- J. Li, J. Jannotti, D. Couto, D. Karger and R. Morris, (2000) ‘A scalable location service for geographic ad hoc routing’, *Proc. of Mobicom’00*, pp.120-130.
- L. Zou, M. Lu, and Z. Xiong, (2005) ‘A distributed algorithm for the dead end problem of location-based routing in sensor networks’, *IEEE Trans. Vehicular Technology*, July, vol. 54, pp. 1509-1522.

- R.C. Shah, A. Wolisz, and J.M. Rabaey, (2005) ‘On the performance of geographical routing in the presence of localization errors’, In *Proc. of IEEE ICC’05*, May, Seoul, Korea.
- C. Intanagonwiwat, R. Govindan and D. Estrin, (2000) ‘Directed diffusion: A scalable and robust communication paradigm for sensor networks’, in the *Proc. of MobiCom’00*, August, Boston, MA.
- A. Valera, W. Seah and S. Rao, (2005) ‘Improving Protocol Robustness in Ad Hoc Networks through Cooperative Packet Caching and Shortest Multipath Routing’, *IEEE Transactions on Mobile Computing*, Sep., vol.4, no.5, pp.443-457.
- K. Akkaya and M. Younis, (2004) ‘Energy-aware routing of time-constrained traffic in wireless sensor networks’, *Journal of Communication Systems*, vol. 17, pp. 663-687.
- M. Chen, T. Kwon and Y. Choi, (2006) ‘Energy-efficient Differentiated Directed Diffusion (EDDD) for Real-Time Traffic in Wireless Sensor Networks’, *Elsevier Computer Communications*, Jan, Vol. 29, No. 2 , pp. 231-245.
- B. Chen, K. Jamieson, H. Balakrishnan and R. Morris, (2001) ‘Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks’, *Proc. Seventh Ann. International Conf. Mobile Computing and Networking*, July.
- C. Schurgers, V. Tsiatsis, S. Ganeriwal and M. Srivastava, (2002) ‘Optimizing Sensor Networks in the Energy-Latency-Density Design Space’, *IEEE Trans. Mobile Computing*, Jan, vol. 1, no. 1, pp. 70-80.
- M. Chen, (2004) ‘OPNET Network Simulation’, *Press of Tsinghua University, China*, April, ISBN 7-302-08232-4.
- L. Feeney and M. Nilsson, (2001) ‘Investigating the energy consumption of a wireless network interface in an ad hoc networking environment’, in *Proc. of IEEE INFOCOM’01*, April, pp.1548-1557.
- M. Chen, T. Kwon, Y. Yuan, Y. Choi and V.C.M. Leung, (2007) ‘Mobile Agent-Based Directed Diffusion in Wireless Sensor Networks’, *to appear in EURASIP Journal on Advances in Signal Processing*.
- M. Chen, V.C.M. Leung, S. Mao and Y. Yuan, (2007) ‘Directional Geographical Routing for Real-Time Video Communications in Wireless Sensor Networks’, *to appear in Elsevier Computer Communications*.
- E.O. Elliott, (1965) ‘A model of the switched telephone network for data communications’, *Bell Syst. Tech. J.*, vol. 44, pp.89-109.
- M. Chen, T. Kwon, S. Mao, Y. Yuan, and V.C.M. Leung, (2007) ‘Reliable and Energy-Efficient Routing Protocol in Dense Wireless Sensor Networks’, *to appear in International Journal on Sensor Networks (IJSNet)*.
- S. Lindsey, C. Raghavendra and K. Sivalingam, (2002) ‘Data gathering algorithms in sensor networks using energy metrics’, *IEEE Trans.Parallel Distrib. Systems*, vol.13, no.9, pp.924-935.