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Spatial-Temporal relation-based Energy-Efficient Reliable routing protocol in wireless sensor networks

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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. 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 STEER, each data packet is relayed by broadcasting, and, among the neighbours (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 locally by the spatial information of each neighbour. To quantify the temporal gradient systematically, a spatial-temporal mapping function is proposed. 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.

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1 Introduction

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 (Wan et al., 2005) and RMST (Stann and Heidemann, 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 minimise energy consumption, such as adjusting the number of paths (Ganesan et al., 2002), the number of data copies delivered to the next hop (Deb et al., 2003), the ‘width’ of the forwarding mesh (Ye et al., 2005), or the reporting rate of sensor nodes (Sankarasubramaniam 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. Akkaya and Younis (2004) proposed an energy-aware QoS routing protocol to maximise the throughput of the best-effort traffic while meeting the end-to-end delay constraint of the real-time traffic. Similarly, EDDD (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 neighbour information. This is usually done by exchanging control messages between neighbours, typically in a periodic manner. In position-based schemes, the positions of a node's neighbours are obtained through beaconing. Having the neighbour information, special metrics are used to evaluate each neighbour, and the best neighbour will be selected as the next hop. For example, Directed Diffusion (DD) (Intanagonwiwat et al., 2000) proposes the use of 'gradient' to evaluate the eligibility of a neighbour node as the next-hop node for data dissemination; in GPSR (Karp and Kung, 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 (STEER) routing protocol 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 neighbours 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 neighbours (or node density), which does not generally increase with the network scale or the total number of nodes.

The rest of this paper is organised 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.

2 Related work

Our work is close to that of Zorzi and Rao (2003) and the more recent work by Biswas and Morris (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 (Ganesan et al., 2002; Deb et al., 2003; Sankarasubramaniam et al., 2003; Stann and Heidemann, 2003; Wan et al., 2005; Ye et al., 2005). In these studies, hop-by-hop recovery (Stann and Heidemann, 2003; Wan et al., 2005), end-to-end recovery (Sankarasubramaniam et al., 2003) and multi-path forwarding (Ganesan et al., 2002; Deb et al., 2003; Ye et al., 2005) are the major approaches to achieve the desired reliability. PSFQ (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 neighbours aggressively. PSFQ employs hop-by-hop recovery instead of end-to-end recovery. Stann and Heidemann (2003) 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 work by Ganesan et al. (2002), multiple disjoint paths are set up first, then multiple data copies are delivered using these paths. In work by Deb et al. (2003), a protocol called RelnForM 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 (Ye et al., 2005) uses a path interleaving technique to achieve high reliability. It assigns the amount of credit α to each packet at the source. α 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 (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 (Stann and Heidemann, 2003; Wan et al., 2005) 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 (Sankarasubramaniam et al., 2003) intends to minimise 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 neighbours (obtained through beaconing) and the final destination's location [obtained through a so-called location service (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 neighbourhood (Karp and Kung, 2000; Yu et al., 2001). To route around areas where greedy forwarding cannot be used, Greedy Perimeter State Routing (GPSR) (Karp and Kung, 2000) tries to find the perimeter of the area. Packets are then routed along this perimeter, around the area.

3 Overview of the STEER design

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 neighbour 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 minimise 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 neighbours, STEER will address the resulting dead end problem (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 neighbours. In a very large scale network, the amount of the routing information and neighbour information may pose an additional challenge for the sensors with low storage capacity. With STEER, a sensor node only needs to record the identifier of its next hop node.

Moreover, data caching is an important technique to recover packet loss due to route breakdowns (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.

4 The STEER algorithm

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.

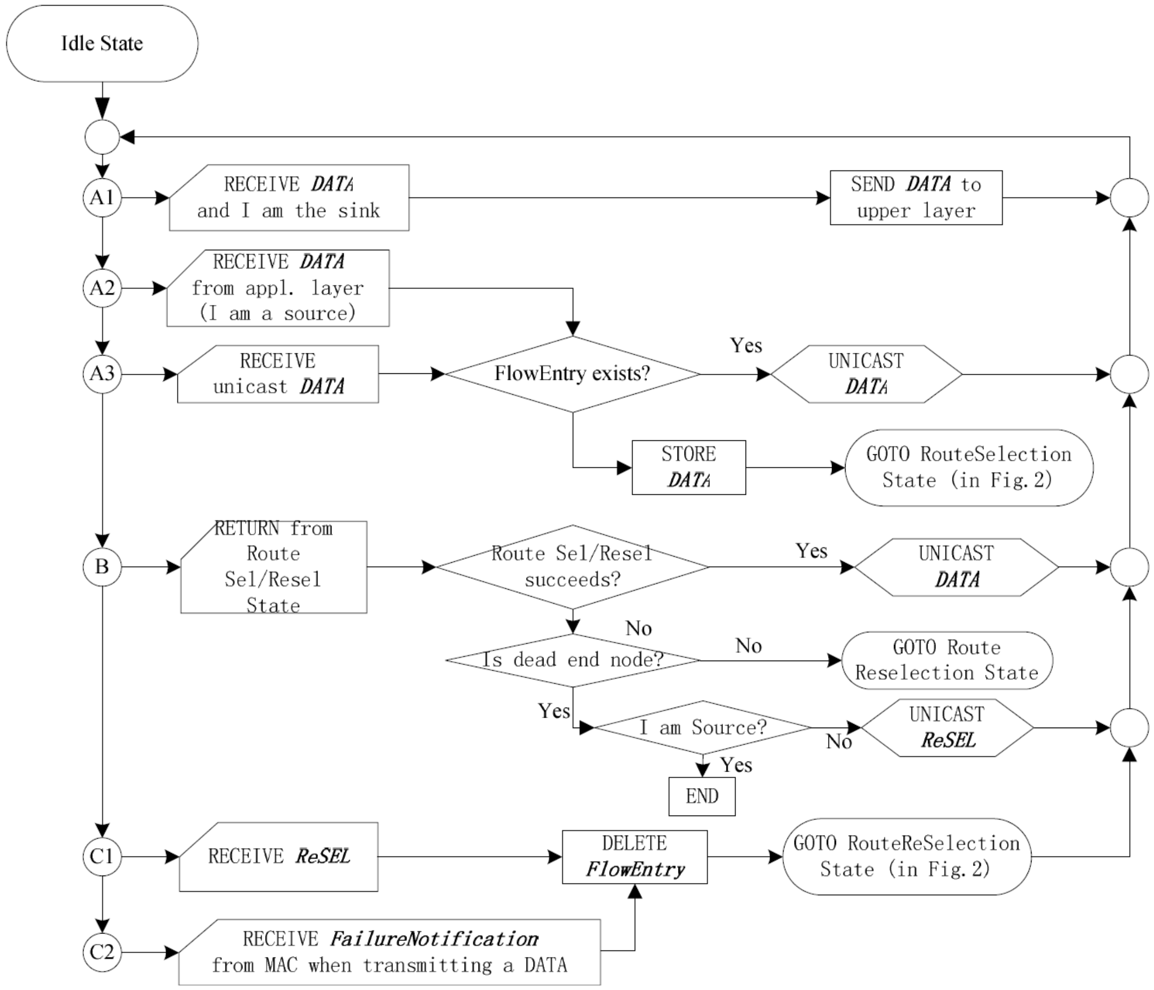
We denote a transmitter (the source or an intermediate node) by '*h*'. The arrival of a sensory data packet (from the application layer of the source node or from the upstream node) triggers *h* to check its flow-entry. Since the flow-entry does not exist initially, *h* stores the data, starts a 'route 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 would not be selected by the transmitter, until it has available neighbours again. The flowchart of the basic STEER Protocol is shown in Figure 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 neighbours, 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 LCs 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.

Figure 1 Flowchart of the basic STEER protocol



Ideally, all the LCs 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 select ion-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 LCs 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 LCs 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.

5 If the RNH receives re-transmitted SEL, it will 'unicast' an 'selection-reply' message (SEL_REP) to node *h*;

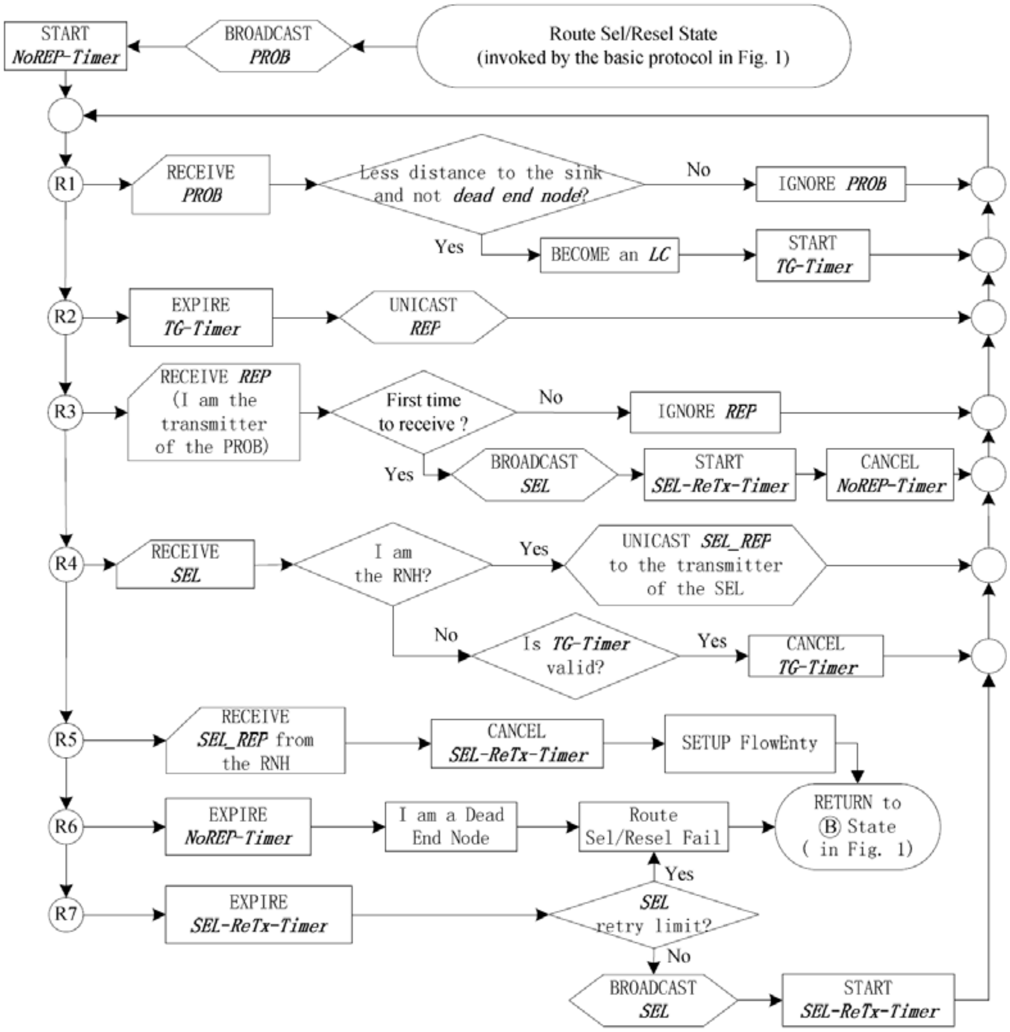
6 If node *h* receives SEL_REP, it will cancel its SEL-ReTx-Timer.

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 Figure 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.

Figure 2 Flowchart of the route selection/reselection (Sel/Resel) mechanism



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 neighbourhood 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 neighbours (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 Figure 3, we assume that LC *i* knows its position $\left(x_i^0, y_i^0\right)$, the position $\left(x_h^0, y_h^0\right)$ of its previous hop *h,* which is piggybacked in the PROB message, and the sink's location $\left(x_t^0, y_t^0\right)$. To obtain the neighbourhood 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 $\left(x_i, y_i\right)$ of *i* can be calculated by equation (1).

$$\begin{cases} x_i = \cos(\alpha)\cdot\left(x_i^o - x_h^o\right) + \sin(\alpha)\cdot\left(y_i^o - y_h^o\right), \\ y_i = \cos(\alpha)\cdot\left(y_i^o - y_h^o\right) - \sin(\alpha)\cdot\left(x_i^o - x_h^o\right), \end{cases} \qquad (1)$$

$$\alpha = \arctan(\frac{y_t^o - y_h^o}{x_t^o - x_h^o}).$$

4.3.2 Optimal Spatial-Temporal Mapping Function (STMF)

After an LC gets its relative coordinates, its eligibility as a next hop node can be determined locally by a certain metric. In Figure 4, we focus on the *N* nodes constituting the subset of LCs above *X*-axis. Recall that an LC is a node that is closer to the sink than its previous hop node. Note that the *N* nodes in Figure 4 represent approximate half of all the LCs. We omit the other half that is below the *X*-axis, for which the same analysis given below is also applicable. The TG of each LC indicates its level of eligibility to be selected as the next hop. We number the LCs in decreasing order of their eligibility level as follows: $1, 2, 3, \cdots, i-1, i, \cdots, N-1, N$.

Figure 3 Obtaining relative coordinates

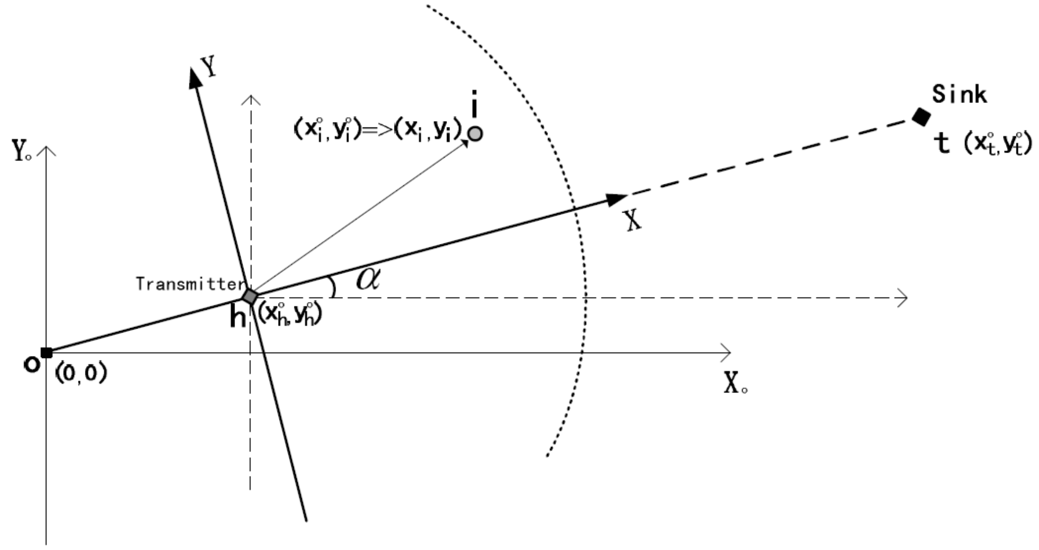
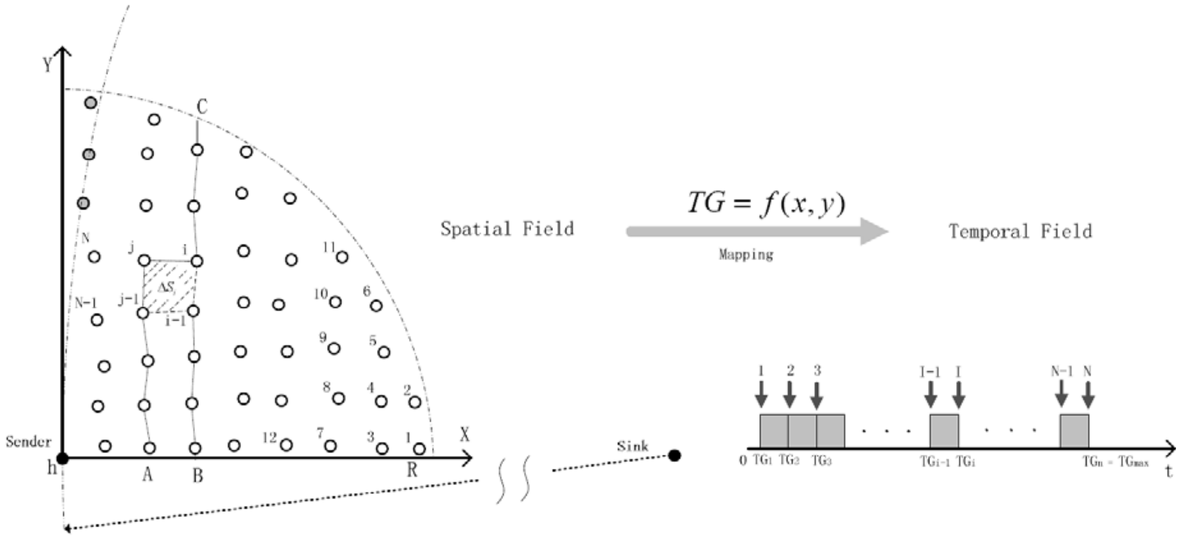


Figure 4 Mapping neighborhood spatial information to temporal information using STMF



The remaining problem is how to find an STMF to calculate TGs which follow the above eligibility order. Based on the relative coordinates, we define an STMF as follows:

$$TG = f(x, y). \tag{2}$$

In Figure 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 Figure 4). We define the gap of the two TGs with successive eligibility orders as follows:

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

ΔTG_i is deemed as the granularity of TG. Here, ΔTG_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, ΔTG_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 ΔTG_i. Thus, a suitable STMF should make ΔTG_i close to T_{REP}, as formulated in equation (4) where $\in$ is a small positive constant.

$$\Delta TG_i \rightarrow T_{REP} + \in, \quad \forall i = 1, 2, \ldots N. \tag{4}$$

In Figure 4, we can divide the forwarding region into N sections, each occupied by a single node. Then let ΔS_i be the size of the area that node i occupies. Assume a certain topology monitoring algorithm (Chen et al., 2001; 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

$$\Delta S_i \rightarrow \Delta S = \frac{A}{N}. \tag{5}$$

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

$$\alpha \Delta S_i \rightarrow TREP + \in . \tag{6}$$

In order to satisfy equation (4), we can set ΔTG_i to $\alpha\Delta TS_i$. Thus, the STMF is obtained as follows:

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

where $g(x) = \frac{x}{2}\sqrt{R^2 - x^2} + \frac{R^2}{2} \arcsin \frac{x}{R}$. In equation (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 Figure 4 is for illustration only. The more regular the topology, the more accurate the approximation in equation (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 (http://www.opnet.com) to evaluate the performance of STEER and compare with GPSR (Karp and Kung, 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 neighbours. If the selected neighbour 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 neighbour 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 discard the packet. The beacon interval is set to 1 sec. 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 (Karp and Kung, 2000). The nodes are randomly placed over a 4000 m × 1500 m 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 250 m. 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 by (Feeney and Nilsson, 2001; Chen et al., 2006; Chen et al., 2007a; Chen et al., 2007b).

We employ the link failure model used Chen et al. (2008). The node failure model is the same as the link failure model An ON-OFF two state Gilbert-Elliot model (Elliott, 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 60 times with different random seeds and get the average results.

Table 1 Simulation setting

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

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 work by (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:

$$\frac{energy \cdot delay}{reliability}. \tag{8}$$

6.1 Impact of TG_{max} in STEER

In these simulation experiments, we change TG_{max} from 0.01 s to 0.05 s 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.

Figure 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 Figure 6, when TG_{max} is small (e.g. 0.01 s), 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 03 s, e_{steer} decreases again since collisions rarely happen.

In Figure 7, when TG_{max} is small, t_{steer} is high because of the following two reasons: (1) collisions between REPs transmitted by LCs with similar TGs collide preventing LCs with relatively high eligibility to become a next-hop node, (2) 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 ms. It is unnecessary to further increase TG_{max} more if the value is large enough to differentiate the LCs, since a large TG_{max} also increase the time for next hop selection. Figure 8 shows that the optimal value TG_{max} = 25 ms gives the best integrated performance.

Figure 5 Impact of TG_{max} on reliability

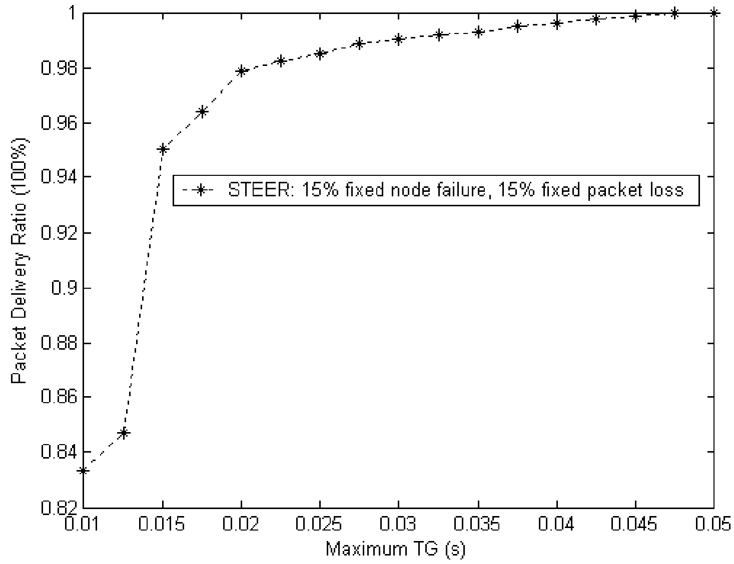


Figure 6 Impact of TG_{max} on energy consumption

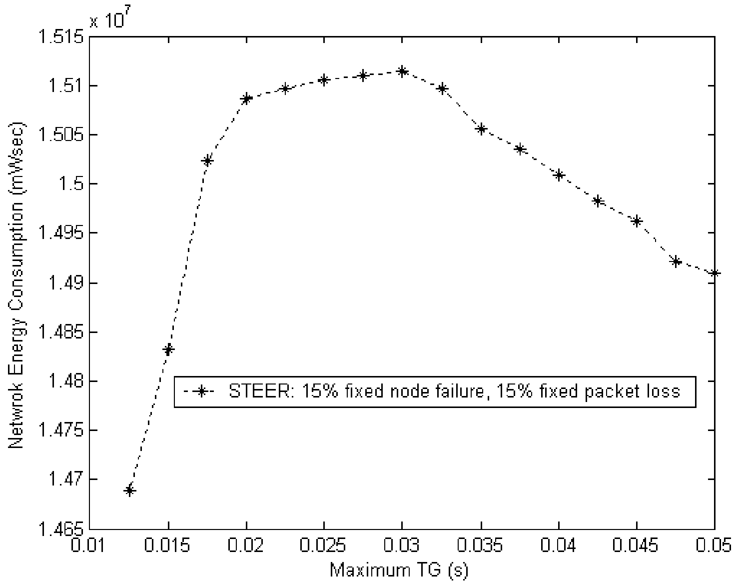


Figure 7 Impact of TG_{max} on end-to-end packet delay

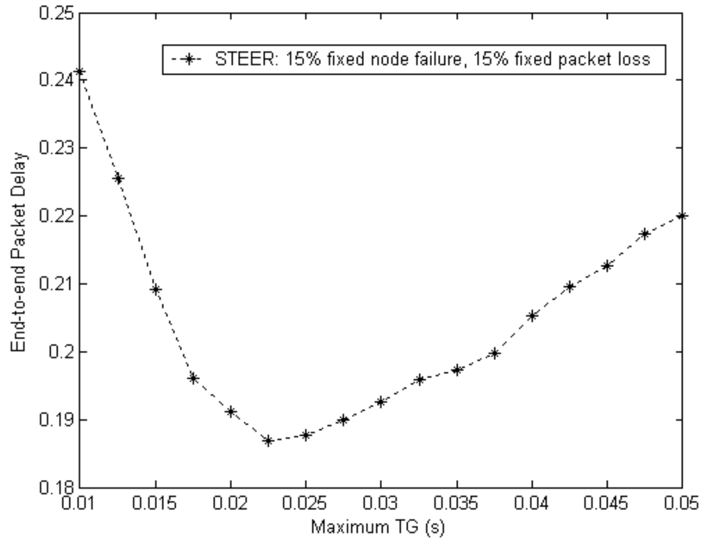
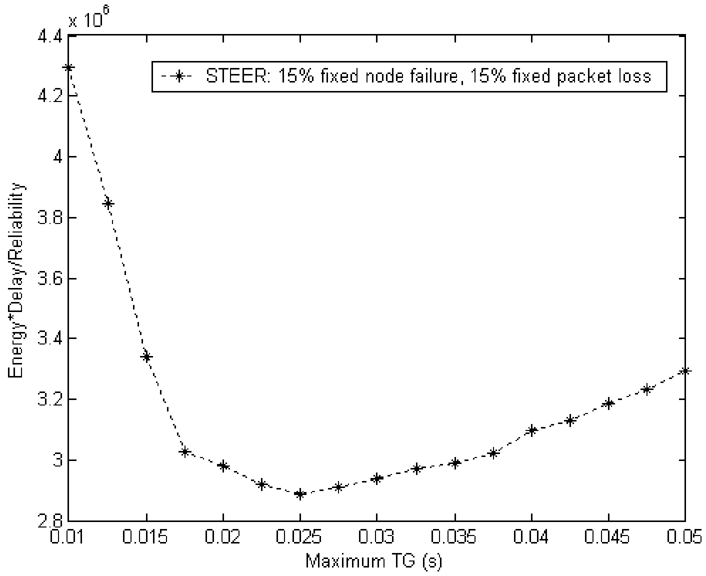


Figure 8 Impact of TG_{max} on $\frac{Energy * Delay}{Reliability}$



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.

Figure 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 performance of STEER is similar for a similar node failure rate and packet loss rate.

Figure 10 indicates that when the loss rate is relatively low, 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 Figure 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 neighbour 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 repeats 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 occurs 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 Figures 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 $Energy \cdot Delay / Reliability$ of STEER in Figure 12 is always lower than that of GPSR.

Figure 9 Comparison of reliability

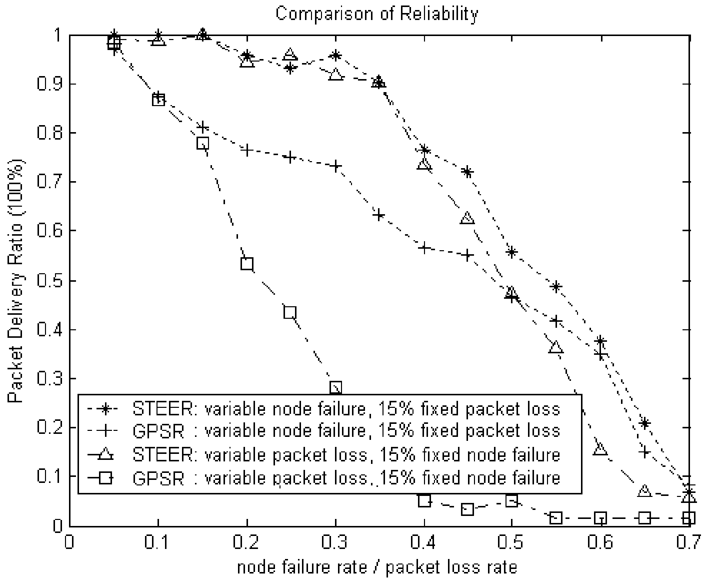


Figure 10 Comparison of network energy consumption

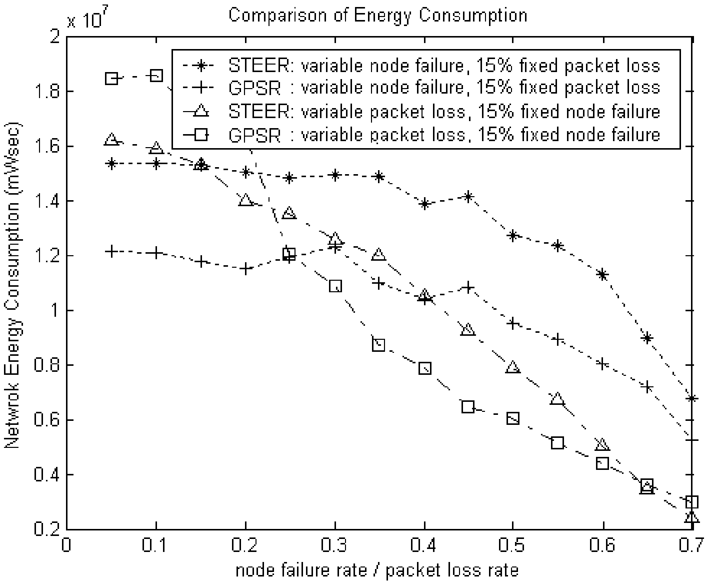


Figure 11 Comparison of end-to-end packet delay

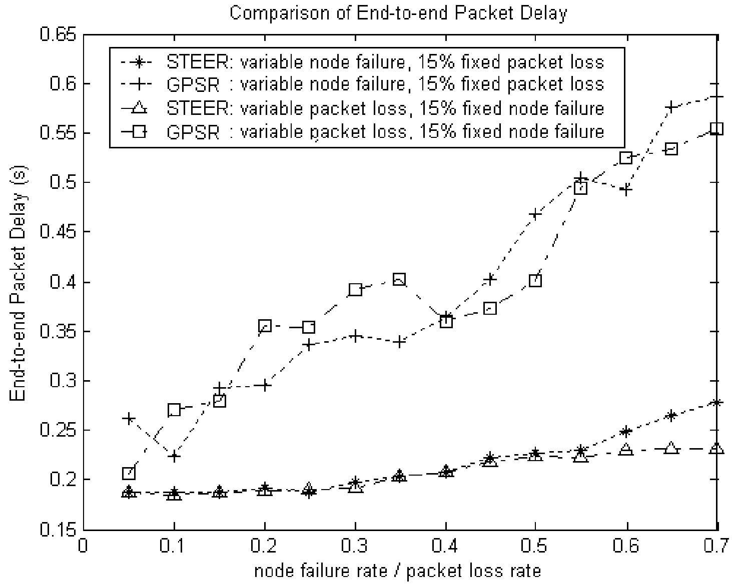
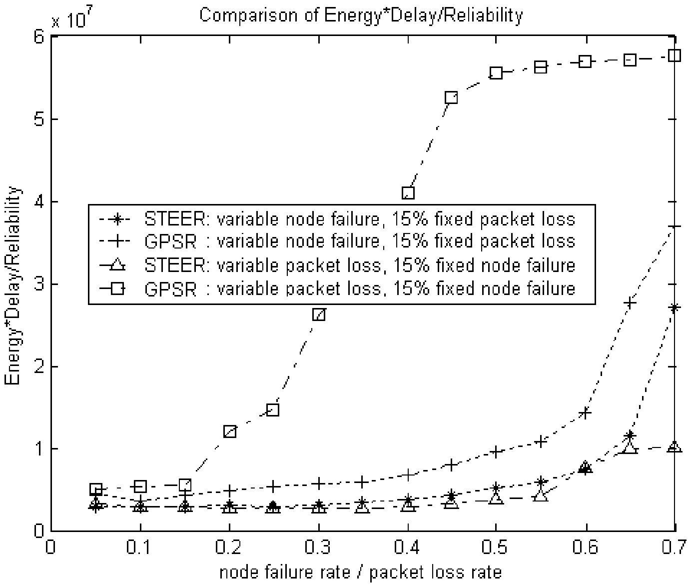


Figure 12 Comparison of energy*delay/reliability



7 Conclusions

Traditional routing protocols in WSNs suffer from several drawbacks caused by outdated neighbour 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 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 neighbourhood. 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 neighbours 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 occurs 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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