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Virtual Coordinates Based Routing in Wireless Sensor Networks

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Recently, position-based routing protocols have been proposed for efficient data dissemination in sensor networks. Routing of packets is done based on the positions of nodes in the neighbor table. One node is selected as a next hop according to the applied routing strategy, e.g., distance-based strategy or direction-based strategy. This paper proposes a virtual coordinates based routing (VCR) scheme, which adopts a new criterion based on virtual coordinates converted from the absolute coordinates. The results of extensive simulation experiments show that VCR achieves an efficient trade-off between energy consumption and end-to-end delivery latency. The overall performance of VCR in terms of energy consumption and end-to-end delivery latency is better than that of both conventional distance-based and direction-based algorithms.

Keywords: Geographical Routing, Virtual Coordinates, Wireless Sensor Network.

RESEARCH ARTICLE

1. INTRODUCTION

Recent years have witnessed a growing interest in deploying a sheer number of micro-sensors that collaborate in a distributed manner on data gathering and processing.[1,2] Sensors are expected to be inexpensive and can be deployed in a large number to harsh environments, which implies that sensors are typically operating unattended. Routing in such networks is a challenging task due to frequent topology changes and limited resources. A lot of topology-based routing protocols (e.g., Directed Diffusion[3]) have been proposed that establish routes on-demand. However, flooding of control packets is costly in terms of battery power and bandwidth.

Position information available at each node is the key enabler for a new class of protocols, called position-based routing protocols. Position-based routing protocols exploit location information to enhance routing and do not route packets solely based on node identifers. Forwarding decisions are based on absolute position of the current node (e.g., provided by GPS), the positions of neighboring nodes (by receiving periodically transmitted hello messages, called beacon) and the sink (e.g., obtained via a location service.[4]) Each packet is routed independently at each node and forwarded in a greedy manner to a neighboring node that reduces the distance to the sink. If a node does not have any neighbors closer to the sink, a recovery mechanism is applied to recover from this local minimum. We only focus on the greedy part of the forwarding in this paper.

There are two basic greedy forwarding strategies, i.e., distance-based strategy and direction-based strategy. In distance-based strategy, the routing protocols[5,6] select the node closest to the sink as a next hop; In direction-based strategy, the routing protocols[7] select the node, whose deviation angle from the line connecting its previous hop node and the sink, is minimum. This paper proposes the virtual coordinates based routing (VCR) scheme, which adopts a new criterion based on virtual coordinates converted from the absolute coordinates. In VCR, the point, which is maximum transmission distance R away from the current node and located in the line connecting current node and the sink, is defined as *strategic location*. Based on the virtual coordinates, the distance of a neighbor to the strategic location is calculated. VCR intends to select the nearest node to the strategic location. To our knowledge, no such criterion has been proposed in previous work.

The result of extensive simulation experiments show that VCR achieves an efficient trade-off between energy consumption and end-to-end delivery latency. The overall performance of VCR in terms of energy consumption, and end-to-end delivery latency is better than both conventional

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distance-based and direction-based algorithms. The rest of the paper is organized as follows. Section 2 presents related work. We describe VCR design issues and algorithm in Section 3. Simulation model and experiment results are presented in Section 4. Finally, Section 5 concludes the paper.

2. RELATED WORK

Geographical (position-based) routing[5,6] is a routing scheme where packet forwarding is performed based on the locations of the network nodes. These protocols are inherently more robust to changes in the network topology than topology-based routing protocols because in the case of topology changes they only require local rerouting by simply selecting another neighbor as the next hop if the previously selected neighbor is no longer available. These protocols furthermore naturally support geocasting.[8] The overview of position-based routing algorithms and location services can be found in Refs. [9] and [10].

The most popular forwarding method used in position-based routing schemes is greedy forwarding, where forwarding decisions are made locally based on information about each node's one-hop neighborhood.[5,6] Greedy Perimeter State Routing (GPSR) forwards each packet to a neighbor closer to the sink than the forwarding node itself until the packet reaches the sink. The scheme works as follows: each node broadcasts a hello message periodically during the network operation to notify its neighbors of its position changes; then, each node knows the positions of its one-hop neighbors and sets up a neighbor information table; a node h that wishes to forward a packet to the sink t simply selects a neighbor with maximum progress from the neighbor information table. In Figure 1, if a neighbor i is selected as the next hop node, the packet progress is given by: $P(h; t; i) = \mathrm{dist}(h; t) - \mathrm{dist}(i; t)$. The neighbor with maximum P is selected as the next hop node. In the case of $P \leq 0$, the greedy forwarding cannot be used, the protocol hereby applies the famous face routing where packets are routed according to the right-hand rule on the faces of a locally extracted planar subgraph[7] to find the perimeter of the area. Packets are then routed along this perimeter, around the area.

On the other hand, direction-based scheme (e.g., compass routing[7]) considers the deviation angle. As an example in Figure 1, the deviation angle ϕ of a neighbor j is the angle between the line connecting h with j and the line connecting h with t. The neighbor with minimum deviation angle will be selected as the next hop node. Compared with distance-based scheme, direction-based scheme intends to obtain a path with shorter Euclidean distance, however, more hop counts are needed.

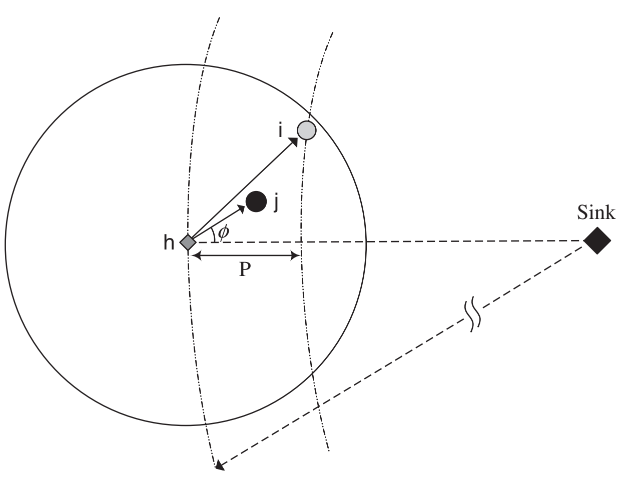

Fig. 1. Illustration of distance-based and direction-based schemes.

3. VIRTUAL COORDINATES BASED ROUTING IN WIRELESS SENSOR NETWORKS

In this section, we discuss the key design issues of virtual coordinates based Routing (VCR). We first present how to obtain *virtual coordinates* in Section 3.1. The *virtual coordinates* is used to make routing decision in Section 3.2. Finally, Section 3.3 illustrates how to handle the dead end problem.

3.1. Obtaining Virtual Coordinates

In most position-based routing approaches, the minimum information a node must have to make useful routing decisions is its position, the position of its neighbors (through beaconing), and the sink's location. The absolute geographical location is obtained by means of GPS. In the global coordinate system of Figure 2, o is the origin; h is the node initiating next hop selection. The absolute coordinates of node h (x_h^o, y_h^o) is piggybacked in the packet transmitted by h. Thus, a neighbor node i knows the position of its upstream node h (x_h^o, y_h^o), its own position (x_i^o, y_i^o), and the sink's location (x_t^o, y_t^o).

In this paper, *virtual coordinates* of a node (e.g., i in Fig. 2) is defined as the coordinates in the virtual two-dimensional coordinate system where the node's upstream node (e.g., h in Fig. 2) is the origin, and the X-axis is the

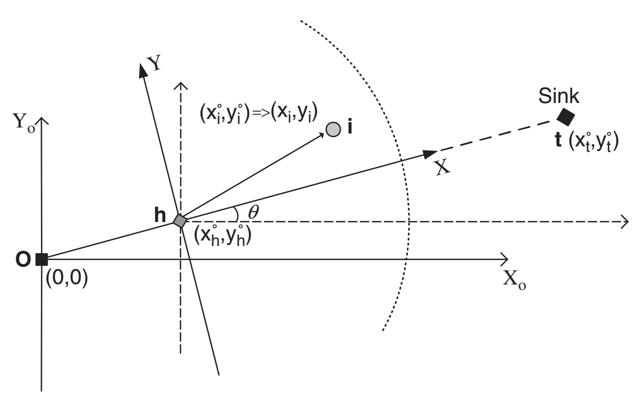

Fig. 2. Obtaining virtual coordinates by means of GPS.

line between the upstream node (e.g., h in Fig. 2) and the sink. As the example shown in Figure 2, the *virtual coordinates* of i is denoted by (x_i, y_i), which can be calculated by Eq. (1).

$$\begin{cases} x_i = \cos(\theta)\cdot(x_i^o - x_h^o) + \sin(\theta)\cdot(y_i^o - y_h^o), \\ y_i = \sin(\theta)\cdot(x_i^o - x_h^o) - \cos(\theta)\cdot(y_i^o - y_h^o), \\ \theta = \arctan\left(\dfrac{y_t^o - y_h^o}{x_t^o - x_h^o}\right) \end{cases} \tag{1}$$

3.2. Routing Decision Based on Virtual Coordinates

In Figure 3, the point $(R, 0)$ is called strategic location, which is R away from the upstream node h and located in the line between h and the sink to maximize hop length. In real conditions, of course, it is impractical to assume that a neighbor node is located at the strategic location. A simple solution is to select the nearest node to the strategic location. The shadow area in Figure 3 is deemed as VCR selection area, where a neighbor node's eligibility as the next hop is evaluated by the criterion based on *virtual coordinates*. A threshold DT $(0 < DT < R)$ is set to limit the VCR-selection-area. Since VCR-selection-area cannot cover the whole greedy forwarding area, the left area is deemed as the normal greedy forwarding area where the node closer to the sink has higher possibility to be selected as the next hop node. Let ΔD be the distance between node i and the strategic location $(R, 0)$. Then, ΔD is derived in Eq. (2).

$$\Delta D = \sqrt{(x_i - r)^2 + (y_i)^2} \tag{2}$$

ΔD is deemed as the basic criterion of VCR scheme. In order to adjust the impacts of y_i on a neighbor's eligibility of being selected as the next hop node, a weighted criterion is derived in Eq. (3).

$$\Delta D_\alpha = \sqrt{(x_i - r)^2 + \alpha(y_i)^2} \tag{3}$$

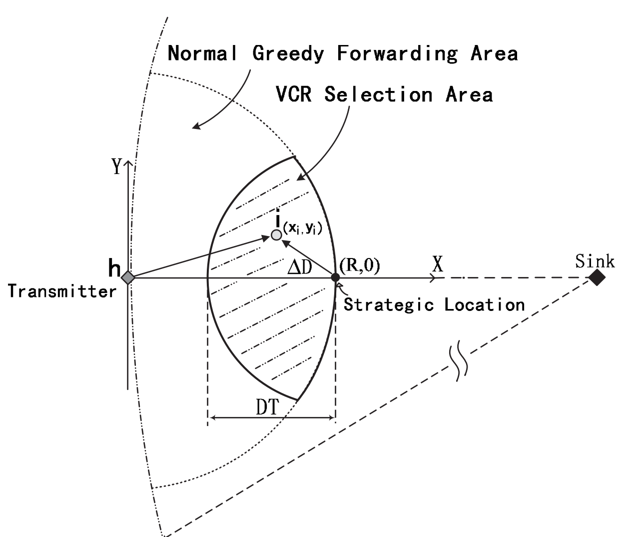

Fig. 3. The VCR selection area.

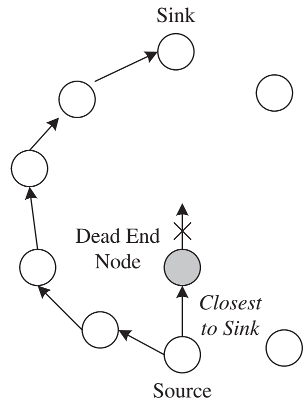

Fig. 4. Illustration of dead end problem.

As the extreme cases, $\alpha = 0$ means that VCR works like distance-based schemes; $\alpha \to \infty$ means that VCR operates like direction-based schemes.

3.3. Handling the Dead End Problem in Sensor Networks

The so-called dead end problem[11, 12] arises when a packet is forwarded to a local optimum, i.e., a node with no neighbor of closer hop distance to the sink as illustrated in Figure 4. In VCR, if there are no neighbors in VCR-selection-area, it will enter greedy mode to select the node among all its neighbors in the normal greedy forwarding area that is geographically closest to the sink. If a node does not have any neighbor closer to the sink in the greedy mode, VCR meets the dead end problem and the packet is forwarded in recovery mode, i.e., the packet is routed according to the right-hand rule to recover from the local minimum.[5] The right-hand rule is a well-known concept for traversing mazes. To avoid loops, the packet is routed in recovery mode on the faces of a locally extracted planar subgraph, namely the Gabriel graph. The packet returns to greedy mode when it reaches a node closer to the sink than the node where the packet entered the recovery mode. Furthermore, if the node has neighbor(s) located in the VCR-selection-area again, the packet switches to VCR routing rather than greedy routing.

4. SIMULATION AND RESULTS

In order to demonstrate the performance of VCR, we compare it with GPSR[5] and CR[7] via extensive simulation studies. In Section 4.1, we present the simulation settings and performance metrics. Our simulation results will be presented in Section 4.2.

4.1. Simulation Methodology

We use OPNET[14] for discrete event simulation. We use IEEE 802.11 DCF as the underlying MAC. Four thousand sensor nodes are randomly placed over a

$10000 \text{ m} \times 1000 \text{ m}$ area. The sensor nodes are battery-operated except the sink. The sink is assumed to have infinite energy supply. The sink locates at one side of the area, while the source is specified at the other side. The rectangular shape of the simulation area is chosen to obtain longer paths, i.e., a higher average hop count. We assume both the sink and sensor nodes are stationary. Each source generates sensed data packets using a constant bit rate with a 1 second interval. The beacon interval is set to 10 seconds.

The basic settings are common to all the experiments. To decrease the influence of one special topology on the results, each experiment is repeated 10 times with different topologies; For each result, we simulate for 20 times with different random seeds. For the evaluation, the mean values of these 10×20 runs are taken.

In this section, four performance metrics are evaluated:

• *Average End-to-End Packet Delay*—It is denoted by T_{ete}. It includes all possible delays during data dissemination, caused by queuing, retransmission due to collision at the MAC, and transmission time.

• *Average Hop Counts*—It is the number of hop counts of a path from the source to the sink.

• *Average Path Energy*—It is denoted by e. It is the energy consumption per successful data delivery. Let N be the number of hop counts of a path. Let d_i be the hop distance of the ith hop. Let e_{ctrl} be the energy consumption of control messages exchanged for a successful data transmission. Let C be a constant which depends on the size of sensed data and the energy consumption for transmitting a bit. Then, the path energy is equal to:

$$e = \sum_{i=1}^{N} [C \cdot (d_i)^2 + e_{\text{ctrl}}] \quad (4)$$

• *Energy*Delay/Reliability*—In sensor networks, it is important to consider both energy and delay. In Ref. [15], the combined energy*delay metric can reflect both the energy usage and the end-to-end delay. In this paper, we adopt the following metric to evaluate the integrated performance of energy and delay:

$$\eta = e \cdot T_{\text{ete}} \quad (5)$$

4.2. Performance Evaluation

In Section 4.2.1, we examine the impact of α on the VCR performances. In Section 4.2.2, GPSR, CR, and VCR are evaluated with varying maximum transmission range R.

4.2.1. Effect of α on the VCR Performance

In these experiments, we change α from 2^{-7} to 2^{7} with all the other parameters in Table I unchanged.

In Figure 5, delay of VCR increases with α increased. The larger is α, VCR works more like direction-based

Table I. Simulation setting.

Basic specification	
Network size	$10000 \text{ m} \times 1000 \text{ m}$
Topology configuration mode	Randomized
Total sensor node number	4000
Data rate at MAC layer	1Mbps
Transmission range of sensor node	Default:100 m
Sensed traffic specification	
Size of sensed data	Default: 1 K bytes
Size of control message	Default: 128 bytes
Sensed data packet interval	1 s
Node beaconing interval	10 s
VCR specification	
α	Default: 1
DT	Default: $2R/3$

scheme, and the smaller hop distance is yielded. Thus, the larger number of hop counts and delay are introduced. In Figure 6, the curve of hop counts exhibits the similar trend with that of delay.

In Figure 7, energy of VCR decreases with α increased. The smaller is α, VCR works more like distance-based scheme, and the larger progress and hop distance is yielded. Since the energy is proportional to the square of hop distance, the larger energy is consumed.

In Figure 8, η is a small value when α is between 0.5 and 4. The smaller is η, the better is the integrated performance of VCR. It is necessary to decrease energy consumption if the delay is small enough to provide end-to-end delay guarantee. Thus, the performance of energy saving and QoS of data gathering (i.e., data latency) can be improved by optimizing α in VCR.

4.2.2. Performance Comparison of GPSR, CR, and VCR

In the following experiments, node density will be changed by varying maximum transmission range. Given a maximum transmission range R, the node density is

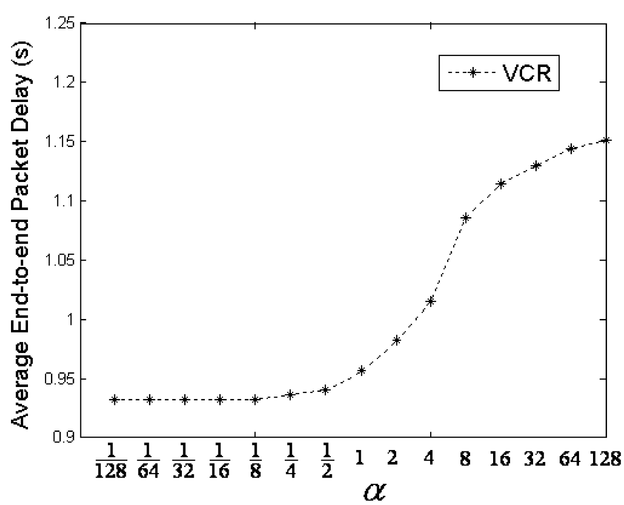

Fig. 5. Comparison of end-to-end packet delay.

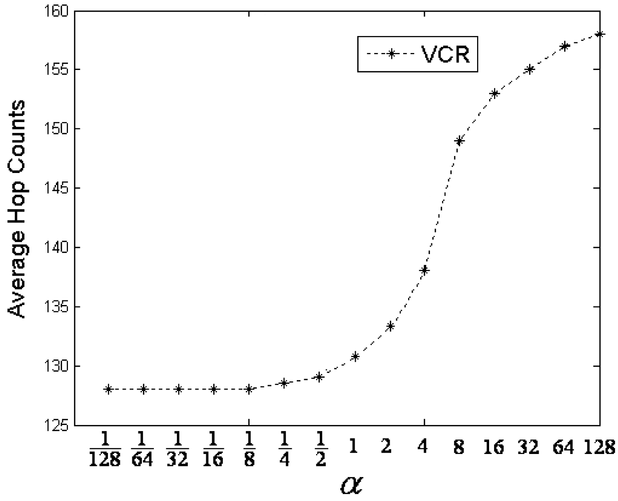

Fig. 6. Comparison of hop counts.

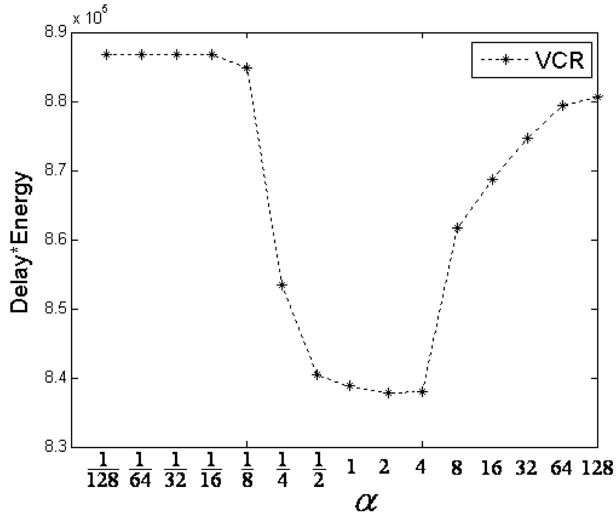

Fig. 8. Comparison of delay*energy.

4000 nodes/$(10000 \times 1000\ \text{m}^2) \cdot \pi R^2$. We change R from 100 m to 250 m.

In Figure 9, the delay of all the schemes decrease with R increased. The larger is R, the less number of hop counts is yielded, and the less delay is obtained. On the other hand, given R fixed, the delay of VCR is close to that of GPSR, and the delay of CR is larger than that of both VCR and GPSR. The responsibility of large delay in CR lies in only considering the effect of direction while ignoring packet progress. Though the small Euclidean path length is obtained in CR, the large number of hop counts and delay are introduced. In Figure 10, the curve of hop counts exhibits the similar trend with that of delay.

In Figure 11, the energy of all the schemes increase with R increased. The larger is R, the larger hop distance is introduced. Though hop count also decreases, the hop distance dominates Eq. (4). Given R fixed, the energy of GPSR is larger than both VCR and CR. GPSR tries to maximize packet progress by introducing large hop distance and Euclidean path length, and it consumes more energy than the schemes considering direction during next hop selection. Though the energy consumption of VCR is larger than that of CR, the delay of VCR is smaller than that of CR.

In addition to compare the schemes in terms of single performance metric, it is important to consider both energy and and delay for the QoS-aware application in WSN. In Figure 12, VCR has the lowest η which illustrates that VCR has better integrated performance than both GPSR and CR. GPSR obtains small delay by sacrificing the energy-efficiency performance, while CR saves energy consumption by introducing large end-to-end packet delay. By comparison, VCR achieves efficient tradeoff between energy and delay than conventional distance-based and direction-based schemes, and exhibits the improved overall performance gain.

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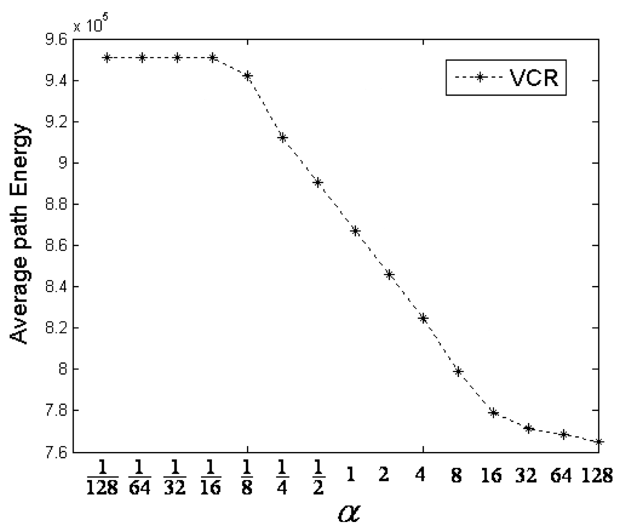

Fig. 7. Comparison of path energy.

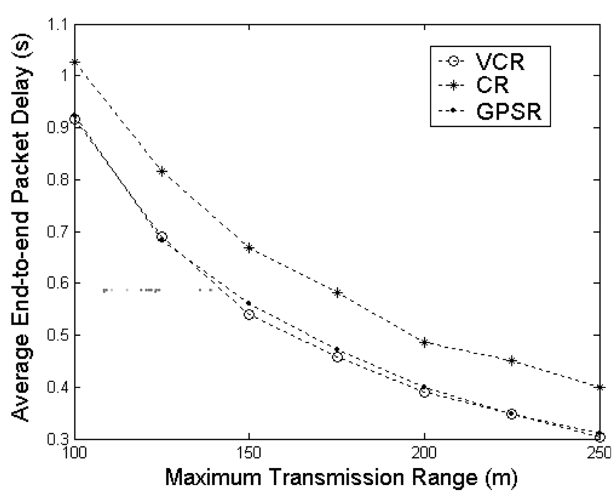

Fig. 9. Comparison of end-to-end packet delay.

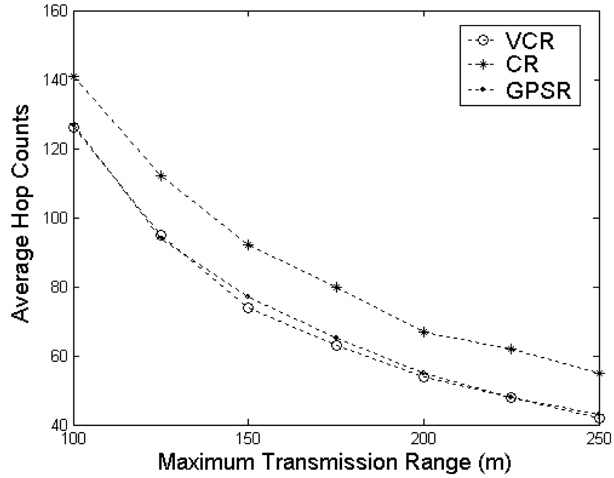

Fig. 10. Comparison of hop counts.

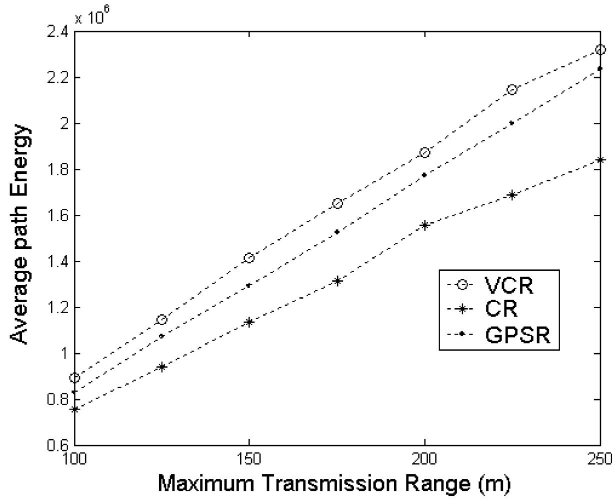

Fig. 11. Comparison of path energy.

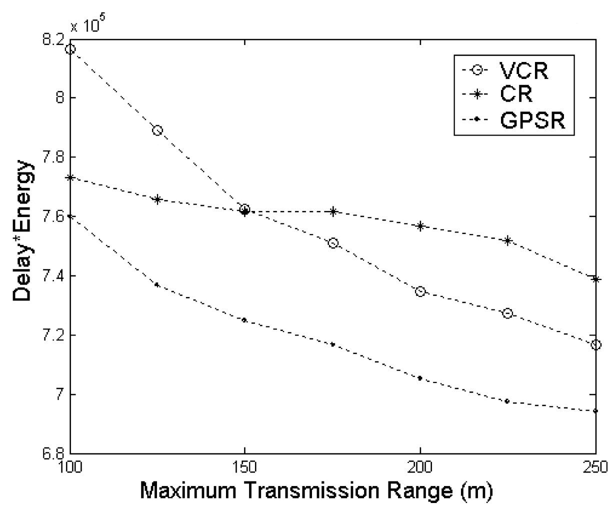

Fig. 12. Comparison of delay*energy.

5. CONCLUSION

This paper proposes virtual coordinates based routing protocol to achieve efficient tradeoff between energy-efficiency and delay performance. In VCR, we first calculate the virtual coordinates of a neighbor according to the absolute coordinates of its previous hop node, itself, and the sink. Then, the distance to the strategic location is calculated based on the virtual coordinates to evaluate the eligibility of the neighbor to work as a next hop node. We divide the greedy forwarding area of a node into VCR-selection area and normal greedy forwarding area. If there are no neighbors in VCR-selection-area, VCR will enter normal greedy mode. We have evaluated the VCR protocol through extensive simulation. According to the simulation results, we observe: (1) By adjusting the value of α, different tradeoff between energy and delay can be obtained; (2) VCR exhibits higher overall performance in terms of energy and delay than GPSR and CR. The extensive simulations also show energy consumption is saved by sacrificing the delay performance. Thus, α should be selected to guarantee the end-to-end packet delay while minimizing the energy consumption by considering the specific application QoS requirement.

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