Adaptive route-sharing protocol for data collection in Wireless Sensor Networks

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Abstract: A Wireless Sensor Network (WSN) comprises a large number of sensor nodes and a few sink nodes. When multiple sink nodes are interested in collecting the readings of the same monitoring region, it is conducive to exploit the sharing route to save bandwidth and power consumption and prolong WSN's lifetime. This paper proposes a Dynamic Route-Sharing Protocol (DRSP), which constructs sharing routes based on different attributes (for example, frequency, packet length or delay time) of the commands requested from different sink nodes. The proposed DRSP dynamically adjusts data transmission route to achieve the goals of routes sharing and route length reduction. The simulation study shows that DRSP saves more energy and bandwidth consumptions than the existing work and thus prolongs the WSN's lifetime.

Keywords: WSN; wireless sensor network; data collection; routing; network lifetime.

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1 Introduction

Wireless Sensor Networks (WSNs) are potentially applied in many fields such as military monitoring, location tracking, environmental sampling and healthcare monitoring. A WSN is mainly composed of few sink nodes and a large number of sensor nodes (Sausen et al., 2009). The sink nodes play the role of interface between users and WSNs, enabling users to dispatch the queries to a region of sensor nodes in a wireless manner. Each sensor node has sensing, computation and wireless communication capabilities. Deployed in the monitoring region, the sensor nodes are responsible for collecting environmental information and reporting their readings according to the queries sent from sink nodes (He et al., 2008). Since sensor nodes are powered by batteries, energy conservation is one of the most important issues in developing routing protocol.

Previous work (Al-Karaki and Al-Malkawi, 2008; Chen et al., 2002) indicated that communication among sensor nodes is the major source of energy consumption. To prolong the network lifetime of the WSN, designing an energy-efficient routing protocol that takes energy consumption into consideration has been a critical issue and has received much attention. Heinzelman et al. (1999) proposed an energy-efficient routing protocol, named LEACH, which uses cluster head to collect the readings from cluster members and then the head forwards the readings to the sink node. Instead of directly transmitting data from each sensor to sink node, the LEACH saves the significant energy consumption. However, a single-hop environment, which means all sensors neighbour to the sink node, is assumed. Furthermore, the energy consumption of LEACH is not efficient in case that cluster head and sink have a large distance.

To improve LEACH, a number of studies (Intanagonwiwat et al., 2003; Sausen et al., 2009; Ye et al., 2005) have proposed energy-efficient routing protocols for a multi-hop WSN. Previous researches (Intanagonwiwat et al., 2002; Kim et al., 2004; Mikami et al., 2006) emphasised the importance of building a shared route between multiple sink nodes and a data source node or between a sink node and multiple data source nodes. Route-sharing protocols were proposed to reduce the total length of shared route so that the energy consumption for data collection can be saved. However, the pre-constructed route cannot be adaptively changed according to the new request of sink nodes.

Kim et al. (2004) adopted a greedy algorithm to construct a shared route for collecting the same data from a specific region to different sink nodes. Then, the branch nodes in the tree filter the data to each route branch according to the frequencies defined by the sink node. Zeng et al. (1998) proposed a multicast tree topology, which is constructed for gathering data from a sensor, which is the root of the multicast tree. When a sink node intends to join the multicast tree, the sink will send the joining message to the root of the multicast tree, and the root of the multicast tree subsequently relays the joining message to the sensor node on the tree, which is nearest to the sink node. After that, the sensor node will calculate the gravity point to build a sharing route for the new sink node. However, the location of the gravity point might not be deployed any sensor, and hence the gravity point might not be the optimal branch point. Moreover, how to build a multicast tree after finding gravity point is not explicitly stated in the paper. Usually, building such a tree requires flooding operations to attain the goal. A large amount of control packets are thereby produced. On the branch point of each multicast tree, the same data must be periodically updated to support the request of each sink node. Thus, the branch point will encounter the same power-consumption problem existed in research (Bhattacharya et al., 2005), and previous built multicast tree will be destroyed.

This paper proposes a DRSP, which constructs routes based on data requests from multiple sink nodes. The established sharing routes can be dynamically adjusted according to newly built route under cost-efficient condition, improving the share degree among existing routes and hence prolonging the network lifetime.

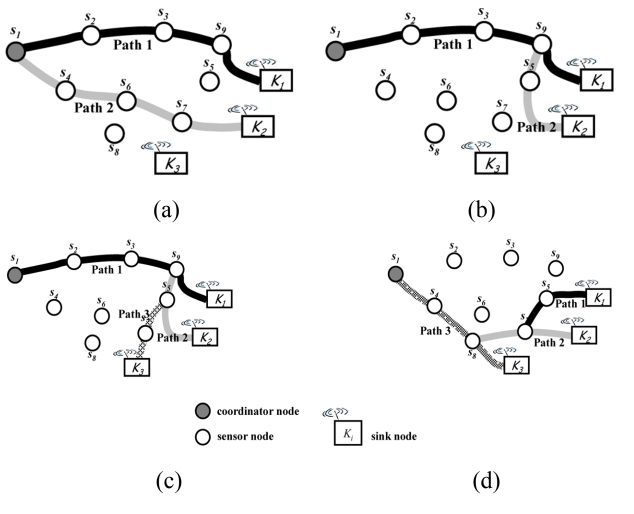
The remaining sections in the paper are organised as follows: Section 2 introduces the related work and basic concepts of the proposed protocol. Section 3 proposes the considered network environment and problem statement while Section 4 details the proposed DRSP. Section 5 compares the performance of DRSP against related work, and finally, a brief conclusion is presented in Section 6.

2 Related work and basic concept

Data collection is the major task of WSNs. On constructing the routes for data collections, researches (Intanagonwiwat et al., 2003; Ye et al., 2005) considered requests sent from multiple sink nodes in different time intervals and aimed to provide data transmission service by establishing different and direct communication routes. However, the route construction did not take the sharing path into consideration, causing energy and bandwidth consumptions. As shown in Figure 1(a), sink nodes K_1 and K_2 apply the routing protocols (Intanagonwiwat et al., 2003; Ye et al., 2005) and build a direct communication route to the coordinator independently. In total, there are seven sensor nodes, including s_1, s_2, s_3, s_4, s_6, s_7 and s_9, participating in the route.

Kim et al. (2004) present a route construction protocol, which considers path sharing to reduce the number of forwarding nodes in the route and thus saves the energy and bandwidth consumptions. As shown in Figure 1(b), the first route is constructed based on the request sent by sink node K_1. After that, another sink node K_2 sends a similar but different request to the coordinator s_1. The routing protocol tries to construct a route that can partially overlap with the existing routes. As a result, there are totally five sensors, including s_1, s_2, s_3, s_5 and s_9, involved in the routes from the coordinator s_1 to sinks K_1 and K_2. The constructed routes have higher degree of path sharing and save sensor nodes s_4, s_6 and s_7. The route sharing not only saves energy and bandwidth consumptions but also avoids the transmission of replicate data on the network, reducing the phenomenon of packet contention and collisions.

Figure 1 The comparison of constructed routes from sink nodes K_1, K_2 and K_3 to coordinator s_1 using different approaches: (a) direct path; (b) two sink nodes sharing path; (c) three sink nodes sharing path and (d) dynamic sharing path (see online version for colours)



Though the sharing route (Kim et al., 2004) can reduce the number of forwarding nodes, however, the degree of route sharing can be further improved. Kim et al. presented the concept that the sink node sequentially connects to the existing routes. The later the sink node sends the data retrieval request to the coordinator, the more difficult for constructing an optimal sharing route since it has a constraint that the latter route should be attached to the existing routes. As shown in Figure 1(c), suppose that the sink nodes K_1 and K_2 have constructed two routes Path 1 and Path 2, respectively. When the sink node K_3 intends to periodically retrieve data from the same coordinator, the proposed protocol will further invite one more forwarding node s_7 to build the new sharing route. Thus, the sharing routes connecting the coordinator to the three sink nodes totally contain sensor nodes s_2, s_3, s_5, s_7 and s_9. However, the constraint that the latter route should be attached to the existing route can be further removed to seek to an optimal sharing route. As shown in Figure 1(d), whenever sink node K_3 intends to retrieve data from the coordinator, a new route can be constructed and the optimal route might be the one that changes the existing routes, enabling the old routes attaching to the new route. As a result, only sensor nodes s_4, s_5, s_7 and s_8 join the route. Compared with the route shown in Figure 1(c), the route constructed in Figure 1(d) saves three forwarding nodes.

The aforementioned example shows that the cost of sharing route and power dissipation cannot be efficiently saved by using greedy algorithm, which aims to attach a new route to the existing one. If the existing routes can be adequately adjusted when constructing a new route, the number of forwarding nodes might be further reduced and hence the energy and bandwidth consumptions for redundant packet forwarding can be saved. This paper proposes a protocol, named DRSP, which builds high degree of sharing routes and enables the data collection to be more energy efficient.

3 Network environment and problem statement

This section presents the network model and assumptions. Some notations that will be used in the proposed DRSP are given.

3.1 Network environment and problem statement

The considered WSN is composed of a few sink nodes, a large number of sensor nodes and a few coordinators. All coordinators and sensor nodes are aware of their own location information. The sensor nodes are responsible for performing monitoring tasks including sensing the environmental information and periodically transmitting their readings to the coordinators according to the sinks' requests. On the basis of user's request, sink node will send command to all the sensor nodes within a specific region so as to meet the requirement of gathering data periodically. The coordinator takes the responsibility of data collection from sensor nodes within the specific region and then proceeds with the data calculation and reports results to the sink nodes. It is permitted that the times of sending requests by different sink nodes can be different. The content of request sent by sink node includes the returning frequency required for data collection, the attributes of the content of the collected data, the expected share degree of data collecting route, the permitted delay time of returning data and the time interval for data collection. Because of the need for returning data periodically, when a sink node sends a request to a coordinator, the coordinator will transmit collected data from itself to the sink node through the constructed route in a multi-hop manner. In the literature, many routing algorithms have been proposed to cope with the problem of how coordinator gathers data from sensor nodes within a specific region in an energy saving and efficient way. This paper would not discuss the issue of gathering data from sensor nodes to the coordinator. Alternatively, we discussed how to build efficient routes with high sharing degree from the coordinator to multiple sink nodes according to their requests.

3.2 Notations

To clearly present the details of the proposed protocol, the following notations are defined. Assume that there are k sink nodes K_i and m sensor nodes s_j in a WSN, where $1 \le i \le k$ and $1 \le j \le m$. Notation R denotes the coordinator. The command requested from each sink node K_i contains the following possible attributes. Notation f_i denotes the required query-frequency and notation a_{ij} denotes the attributes of the content of collected data. The expected share degree of routes for data collection is denoted by l_i. The permitted delay time for each queried data is denoted by d_i. Notation TI_i represents the time interval for data collection. Consider the process that the sink node K_i sends Route Request (*RREQ*) packets to the coordinator R using directional flooding approach. If node s_x sends an *RREQ* packet to node s_y, we refer node s_x to be the upstream candidate of node s_y. A route constructed from sink K to coordinator R is denoted by *Route* $(K, R) = \{K = s_0, s_1, \dots, s_n = R\}$ where s_i denotes the nodes that participate in the route. We further assume that node s_i is the upstream node of node $s_i + 1$, and node $s_i + 1$ is the downstream node of node s_i. Table 1 summarises the notations used in this paper.

Table 1 Notations used in this paper

Notation	*Descriptions*
k	The number of sink nodes
K_i	The ith sink node
m	The number of sensor nodes
s_j	The jth sensor node
R	The coordinator
f_i	The required query-frequency of sink K_i
a_{ij}	The attributes of requested by sink K_i
l_i	The expected share degree of routes from sink K_i
d_i	The permitted delay time requested by sink K_i
TI_i	The time interval for data collection requested from sink K_i

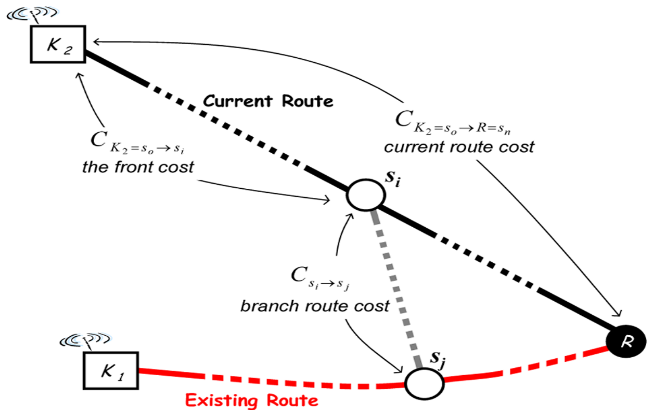
The so-called existing route denotes a built route from some sink nodes to the coordinator while the current route denotes an under-constructed route from the new sink node to the coordinator. Let current node denote the sensor node that is on the current route and executes the route construction task.

Let the existing forwarding node denote the sensor node that is on the existing route. Moreover, to construct a low-cost sharing route, notation $C_{\overline{xy}}$ is defined as the cost of $link_{\overline{xy}}$, which is measured by the cost of power consumption and time delay. Let $C_{i \to j}$, denote the cost of a route from sensor node s_i, to node s_j, we have

$$C_{i \to j} = \sum_{k=i}^{j-1} C_{\overline{s_k s_{k+1}}}. \quad (1)$$

As shown in Figure 2, we define the terms of the cost for each route. The current route cost $C_{K_2 = s_o \to R = s_n}$ denotes the cost for building route between sink node K_2 and coordinator R. On the current route, the cost of the route from sink node K_2 to current node s_i is referred as the *front cost* of current route or the *front cost* in short, and is denoted by the symbol $C_{K_2 = s_o \to s_i}$. Furthermore, the cost of route between current node s_i and existing forwarding node s_j is referred as *branch route cost*, and is denoted by $C_{s_i \to s_j}$.

Figure 2 The illustration of the cost of different routes (see online version for colours)



4 Dynamic Route-Sharing Protocol

This paper focuses on the route construction between multiple sinks and one coordinator and proposes a DRSP. The proposed DRSP protocol is composed of three major Phases: Route Request, Route Reply and Route-Sharing Phases. In the Route Request Phase, a sink node sends user's commands to coordinator by applying directional flooding operations in a multi-hop manner. Then, an initial route will be built between the sink node and the coordinator in the Route Reply Phase. After that, the Route-Sharing Phase will dynamically adjust the constructed route to establish an optimal sharing route according to the cost calculation. The following describes the details of DRSP.

4.1 Route request phase

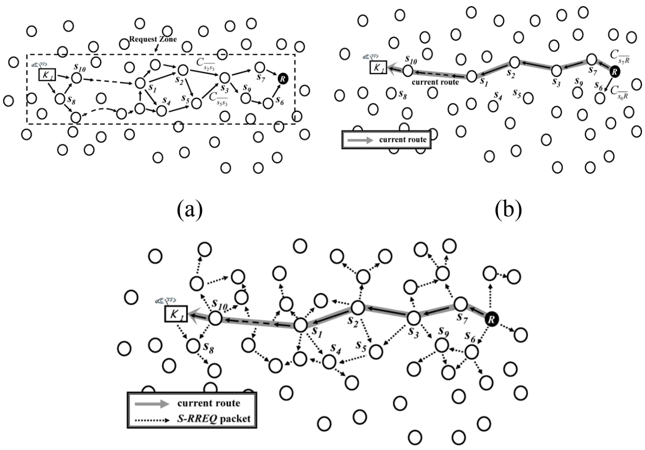
When any user issues a command to a certain sink node K_i, the sink node K_i will initiate the Route Request Phase. In this phase, the sink node K_i sends *RREQ* to the coordinator *R* using directional flooding approach in a multi-hop manner. Figure 3 depicts the format of *RREQ* packet, which contains the query request of data collection parameters sent from sink node. An *RREQ* packet is composed of several fields including sink ID and coordinator ID, frequency, attributes, share degree, delay time and time interval. In addition, the *RREQ* packet also contains the information of upstream candidate including its ID, remaining energy and the front cost of sender.

Figure 3 The packet format of the *RREQ*

Sink_ID	Coordinator_ID	$F_{current}$	Attributes	Share degree	Delay time	Time interval	Sender_ID	E_{rem}	$C_{sink \to s}$

To relay the *RREQ* packets to the coordinator *R* as soon as possible but avoid the packet flooding over the entire sensor network, *DRSP* will allow the *RREQ* packet to be flooded within a Request Zone, which is defined according to the locations of sink node K_1 and the coordinator. Without the loss of generality, assume that the sink node is located at the right bottom of the coordinator. The Request Zone can be defined as the region where the top left and the bottom right points are the coordinates of coordinator and sink node, respectively. Let C_{lowest} denote the lowest cost from a sink node to a sensor node. Since the sensor in the Request Zone might receive multiple *RREQ* packets and therefore has different front costs, it should record C_{lowest} in its own cost table. Figure 4(a) gives an example to illustrate the operation of Route Request Phase. The sink node K_1 appoints a certain Request Zone to forward *RREQ* packets to coordinator *R*. Assume that node s_3 is located in the Request Zone and first receives the *RREQ* packet from its neighbouring node s_2. In the meantime, sensor node s_3 will treat node s_2 as an upstream candidate and evaluate the costs $C_{\overline{s_2 s_3}}$ and $C_{K_1 \to s_3}$. On the basis of the content of *RREQ*, a new value of the front cost $C_{K_1 \to s_3} = C_{K_1 \to s_2} + C_{\overline{s_2 s_3}}$ is calculated. Since sensor node s_3 first receives the *RREQ* packet, it sets C_{lowest} value to be the front cost $C_{K_1 \to s_3}$ in its own cost table, places $C_{K_1 \to s_3}$ in the fields of *RREQ* packet and records the upstream node to be node s_2. After that, node s_3 sends the *RREQ* packet to its neighbours. Whenever sensor node s_3 receives another *RREQ* packet from node s_5, similarly, sensor node s_3 will treat node s_5 as its upstream candidate, and calculate the front cost $C_{K_1 \to s_3}$. If node s_3 finds that the cost value $C_{K_1 \to s_3} = C_{K_1 \to s_5} + C_{\overline{s_5 s_3}}$ of the route passing through node s_5 is better than the cost $C_{K_1 \to s_3} = C_{K_1 \to s_5} + C_{\overline{s_5 s_3}}$ of the route passing through only node s_2, node s_3 will set C_{lowest} to be the value of $C_{K_1 \to s_5}$, update the upstream node to be node s_3, put the value $C_{K_1 \to s_3}$ in the *RREQ* packet and then send the *RREQ* packet again.

Figure 4 The steps of building routes between sink node K_1 and coordinator *R:* (a) in Request Zone, sink node *K* uses directional flooding approach to send the *RREQ* packet to the coordinator *R*; (b) Coordinator *R* responds *RREP* to the sink node *K* according to the cost table and (c) optimistic node sends *S-RREQ* packet to construct the sharing route (see online version for colours)



(a) (b) (c)

4.2 Route reply phase

In this phase, coordinator *R* will determine a route between sink node K_i and coordinator *R*, and then send back a Route Reply Packet (RREP) to sink node K_i in a multi-hop manner. Moreover, the coordinator will notify sink node K_i whether this is the first route. If it is the case, the route is determined by coordinator *R*. Otherwise, a share route will be further explored. The format of *RREP* is shown in Figure 5. The *Receiver_ID* field records the upstream node whereas the *Destination_ID* field records the sink node that sent the request. In this way, the *RREP* can be transmitted to the sink node in a multi-hop manner. In addition, the First route field records whether there has already existed a route. The $C_{\text{sink}\to R}$, $C_{\text{sink}\to p}$ and $C_{e\to f}$ fields record the current route cost, cost from a sink to a sensor node and branch route cost, respectively, to help determine whether it is worth to construct a share route. The $Hops_{\text{rem}}$ field records the degree of route sharing whereas the F_{current} field records the frequency of data collection requested by the sink node.

Figure 5 The packet format of the RREP

Sender_ID	Receiver_ID	Destination_ID	First route	$C_{sink \to R}$	$C_{sink \to p}$	$C_{e \to f}$	$Hops_{rem}$	$F_{current}$

Figure 4(b) is taken as an example to illustrate the detailed operations of Route Reply Phase. Herein, we assume that sink node K_1 is the first sink node that issues command to the coordinator *R*. The coordinator *R* has two neighbours of upstream sensor nodes s_6 and s_7 at the moment. We further assume that coordinator R can derive the minimal current route cost $C_{K_1 \to R}$ by constructing a route passing through node s_7. Thus, coordinator R will fill the values of $C_{K_1 \to R}$ in the two fields of *RREP*: current route cost and the front cost, and set the first route field in *RREP* to 1. Then, coordinator R sends the *RREP* to sink node K_1 in a multi-hop manner.

Figure 4(c) illustrates the operations of the other situation that sink node K_1 is not the first sink node but issues the command to coordinator. Since there are existing routes to coordinator R, the first route field in the *RREP* is filled in 0 by coordinator R, which informs sink node K_i to exploit the opportunity for building sharing routes and notifies the current node, which is responsible for forwarding *RREP*, to construct sharing routes in its surroundings. Here, we define the *l_i-hop neighbours* of the current node as the *optimistic* node, where value l_i denotes the sharing degrees decided by the sink node. The 1-hop neighbours of coordinator R and current nodes also receive *RREP*. The optimistic nodes will treat *RREP* as *S-RREQ* packet since the first route field in *RREP* is set to 0.

4.3 Route-sharing phase

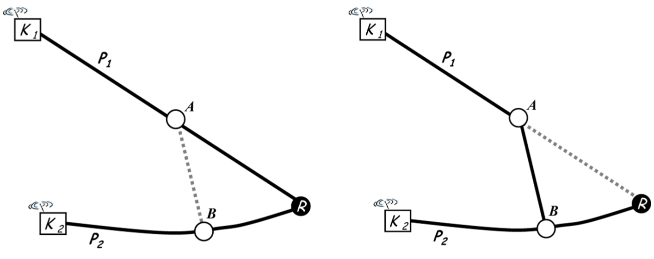
After entering the Route-Sharing Phase, the optimistic nodes will send the *S-RREQ* packet to find outward sharing routes, and the hop distance of sending *S-RREQ* packet outward has followed the value of the share degree l_i field in *RREP*. Therefore, all the sensor nodes within the requested hop count of *S-RREQ* packet will play the role of optimistic node. A forwarding node receiving an *S-RREQ* packet represents the current and existing routes are able to construct a sharing route. Consider two paths P_1 and P_2 as shown in Figure 6(a) where K_1 and K_2 are sink nodes and R is a coordinator. Without loss of generality, we assume that it is worth to change path of P_1 from $\{K_1, A, R\}$ to $\{K_1, A, B, R\}$. That is, we assume that the following expression is satisfied so that it is worth to change path P_1. As a result, paths P_1 and P_2 have sharing segment for saving the redundant data transmissions.

$$C_{K_1 \to A} + C_{A \to B} < C_{K_1 \to R}. \quad (2)$$

Figure 6(b) depicts the sharing path of P_1 and P_2, where $\{B, R\}$ is the shared segment. To describe the detailed operations of *DRSP*, the following defines branch node and attached node. A *branch node* of a shared path is referred to the node that is the first common node of the shared segment. The *attached node* of path P_1 is the first node that changes path P_1 so that P_1 can be attached to path P_2 and therefore the two paths can be merged to construct a common segment. As shown in Figure 6(b), node B is a branch node while node A is an attached node.

In the Route-Sharing Phase, optimistic node will try to find an adequate couple of branch and attached nodes to change the route for achieving the goal of route sharing. Since the requested returning frequency of sink node is not the same as that of coordinator, the following route-changing strategy is given as a foundation for building a sharing route.

Figure 6 The illustration of constructing a sharing path: (a) assume that it is worth to change path from $P_1 = \{K_1, A, R\}$ to $\{K_1, A, B, R\}$ and (b) the branch and attached nodes are nodes B and A, respectively (see online version for colours)



(a) (b)

Criterion 1: When building a sharing route, the route with lower requested returning frequency must be attached to those routes with higher requested returning frequencies.

When the two routes with different returning frequencies intend to retrieve data from the same coordinator at the same time, the route with higher returning frequency can share similar data with the route with lower returning frequency. Criterion 1 helps reduce the cost of data transmission.

Criterion 2: If optimistic node s_j satisfies the following expression (3), it can continue to send *S-RREQ* packet. The forwarding node s_i on the existing route whose cost calculation meets expression (3) returns the request of changing route from the current nodes.

$$C_{K_2 = s_o \to s_i} + C_{s_i \to s_j} < C_{K_2 = s_o \to R = s_n}. \quad (3)$$

In Figure 7, it can be found that after node s_{13} delivers the *RREP* to its upstream node s_{19}, optimistic node s_{14} will treat the *RREP* as *S-RREQ* packet, and check if the cost of the route satisfies the requirements as stated in Criterion 2. If $C_{K_2 \to s_{13}} + C_{s_{13} \to s_{14}} \geq C_{K_2 \to R}$ or $C_{K_2 \to s_{14}} > C_{lowest}$, node s_{14} will stop to send the *S-RREQ* packet. On the contrary, if criterion 2 is satisfied, node s_{14} will update the value of branch route cost in *S-RREQ,* and continue to send *S-RREQ* packet to its neighbouring nodes s_7 and s_{15}, aiming to construct the share route. Similarly, nodes s_7 and s_{15} will decide whether to continue to send *S-RREQ* packet.

As shown in Figure 7, the *S-RREQ* packet is sent to two nodes s_2 and s_3 on the existing route. Then, nodes s_2 and s_3 evaluate whether the cost of route meet the requirement of route adjustment based on Criterion 2, play the role of branch node candidate according to Criterion 1, and then reply to the current node s_{13} with an *S-ACK* message. At this moment, the current node s_{13} is referred as attached node candidate, and branch node candidates s_2 and s_3 will add cost into the fields of *S-ACK* as a reference for optimistic nodes and branch node candidates to further construct the sharing routes. Figure 8 shows the packet format of *S-ACK.* The *Branch_node_candidate_ID* and *Attached_node* *_candidate_ID* fields record the IDs of branch and attached node candidates. The $C_{\text{sink}\to b}$ counts the cost of segment from sink node to branch node candidate. The F_{existing} field records the frequency of the existing route so that the current sink node can figure out the frequency of the existing route. The *Join* field helps to record whether the current route should be connected to the existing route. If it is the case, the value of *Join* field is zero. Otherwise, its value is one.

Figure 7 Sink node K_2 uses *RREP* and *S-RREQ* packet to create possible sharing route (see online version for colours)

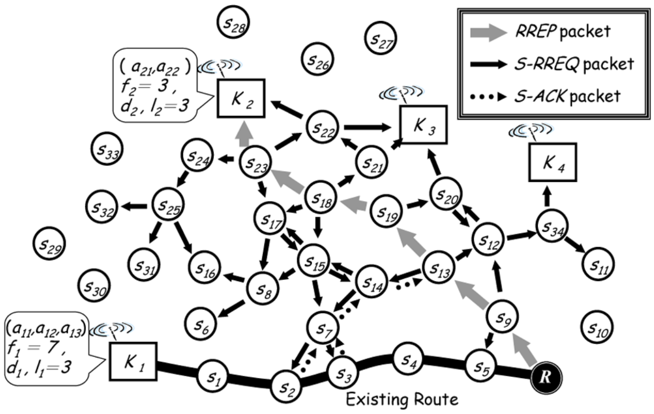


Figure 8 The packet format of the *S-ACK*

Branch _node_candidate_ID	Attached_node_candidate_ID	$C_{sink\to b}$	$F_{existing}$	Join

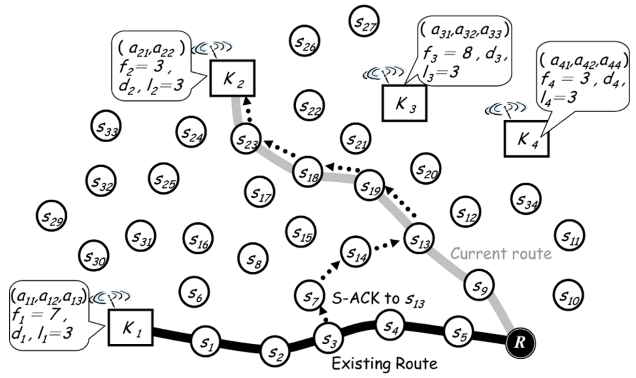
Each current node sends *S-RREQ* packet independently to find possible branch node candidates. For an optimistic node, it might receive different *S-RREQ* packets from different current nodes. As shown in Figure 7, current node s_{18} sends *S-RREQ* packet to the optimistic node s_7 via optimistic node s_{15}. Before deciding to send *S-RREQ* packet, node s_7 will check the *S-RREQ* packet and find that the remaining hop is 1. Node s_7 then checks the value $C_{s_{14}\to s_7}$ and evaluates that the cost of route passing through the optimistic node s_{14} is 22.2 whereas the cost of route passing through the optimistic node s_{15} is 17.6. Thus, the requirement of Criterion 2 is satisfied. The optimistic node s_7 will further continue to forward the *S-RREQ* packet. When current node s_{23} sends *S-RREQ* packet to the optimistic node s_7 via optimistic node s_{15}, it will find that the remaining hop count of *S-RREQ* packet is 0. Thus, optimistic node s_7 will only keep the information in the cost table instead of continuing forwarding *S-RREQ* packet.

The behaviours of sending *S-RREQ* packet and *S-ACK* by the current node and optimistic node might identify multiple couples of attached and branch node candidates. Thus, to decide an optimal couple of attached and branch nodes, the current node, which plays the attached node candidate, will send an *S-ACK* packet to the sink node so that the sink node can select the sharing route with the lowest cost and notify the optimal couple of attached and branch nodes and the coordinator to construct the connections. As shown in Figure 9, upon receiving *S-ACK* sent from branch node candidate s_3, the current node s_{13} will send the *S-ACK* to sink node K_2.

4.4 Adaptive route sharing

Previously, we have mentioned the strategy of building sharing route when current route has sensor nodes with low returning frequency. The following states the case when the returning frequency of current route is higher than that of the existing route.

Figure 9 An example of selecting a branch node candidate (see online version for colours)



Different from the aforementioned strategy, upon receiving the S-RREQ packet, the existing forwarding node, say s_x, will evaluate the necessity of building sharing route between current route and existing route based on the route cost from sink node to both itself and the branch route cost. If it is the case, node s_x will fill the Join field in *S-ACK* with value 1, representing that the existing route will join current route for the sake of forming sharing route. Then, node s_x will play the role of attached node candidate and send the *S-ACK* packet to the current node. Upon receiving the *S-ACK* message, the current node will play the role of branch node candidate and simultaneously forward the *S-ACK* message to the sink node.

Finally, the sink node can determine the best attached and branch nodes from all possible candidates and then notify them and the coordinator to construct the connections. As a result, the existing route with lower frequency can attach to the current route with higher frequency for constructing a more efficient sharing route.

As depicted in Figure 10, suppose the existing forwarding node s_7 receives an *S-RREQ* packet from the current node s_{12}. It is not worth for node s_7 to change the route according to cost evaluation. Upon receiving the *S-RREQ* packet sent from current node s_{20}, the existing forwarding node s_{23} decides to build a sharing route with node s_{20}, and then play the role of attached node candidate. After that, node s_{23} returns an *S-ACK* message to node s_{20} to join current route. Node s_{20} then sends the *S-ACK* to the sink node K_3. Upon receiving the *S-RREQ* packet, the existing forwarding node s_2 helps combine original existing route and the current route as a new sharing route and the original existing route can reduce the cost by changing to a new sharing route. The node s_2 then returns *S-ACK* to node s_{12}

and performs the route-changing scheme to achieve the goal of route sharing.

The proposed protocol tries to build a sharing route for those sink nodes that request to collect the data from the same coordinator. For the data with different attributes, another route to coordinator *R* will be built by sink node itself as shown in Figure 11. We assume that the coordinator *R* chooses nodes s_{10}, s_{11} and s_{34} to forward data from the coordinator *R* to the sink node K_4. However, the common attributes of the requested data by K_4, K_1, K_2 and K_3 are (a_{41}, a_{42}) and there is still a different attribute (a_{44}). After receiving responded *S-ACK* from s_{12}, node s_{34} can know the attributes (a_{41}, a_{42}) of shared data, which is offered by node s_{12}. Node s_{34} then continues to transmit *S-ACK* to sink node K_4. Therefore, sink node K_4 selects node s_{34} to play the role of attached node. After playing the role of attached node, node s_{34} will collect the data with attributes (a_{41}, a_{42}) from the sharing tree and collect the data with attribute (a_{44}) from the route between itself and coordinator *R*. Finally, node s_{34} integrates the data and sends back to sink node K_4.

Figure 10 The existing route formed by sink node K_1 and K_2, and the illustration of steps in building sharing route among sink node K_3 (see online version for colours)

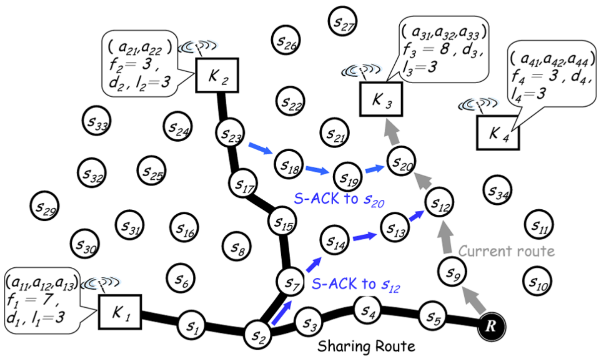
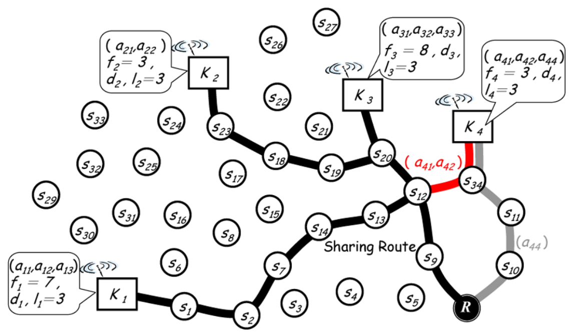


Figure 11 The sharing route that sink nodes K_1, K_2, K_3 and K_4 builds to connect coordinator *R* (see online version for colours)



4.5 Discussions of cost function design

In the section, Cost Function is proposed for each sensor node to calculate the cost of communication with neighbouring nodes at the moment when sensor node receives packets, which is sent from neighbouring nodes. For sink node K_i the request of its query is frequency f_i. Assume that there are δ attributes a_{ij} in the query, where $1 \le j \le a$. If a route built by sink node K_i is $P = \{K_i\, s_0, s_1, \ldots, s_m = R\}$, the distance between s_k and s_{k-1} is r_k, and the residual power of sensor node s_k is $0 \le v_k \le 1$. The cost of route *P* can be denoted by the following expression:

$$Cost(P) = \sum_{k=0}^{m} \left(\sum_{j=1}^{\delta} a_{ij} \times f_i \times \frac{1}{v_k} \times r_k^2 \right). \tag{4}$$

The number of neighbours contending to send data will be the main factor of the delay of packet transmission. Thus, the delay of route *P* can be denoted by the following expression:

$$Delay(P) = \sum_{k=1}^{m} \text{delay}\,(S_k) = \sum_{k=1}^{m} \sum_{x \in N(s_k)} x.\text{route}$$

where

$$x.route = \begin{cases} 1 & \text{if } x \text{ joins a route} \\ 0 & \text{if } x \text{ does not join a route} \end{cases}. \tag{5}$$

From equations (4) and (5), the Cost Function route *P* is:

$$C_p = \alpha \times \text{Cost}\,(P) + (1 - \alpha) \times \text{Delay}\,(P) \tag{6}$$

4.6 The DRSP algorithm

This subsection formally presents the *DRSP* algorithm.

The Dynamic Route Sharing Protocol (DRSP)

Phase I: The Route Request Phase:

Step 1: The sink creates an *RREQ*(*Sink_ID*, *Coordinator_ID*, $F_{current}$, *Attributes*, *Sharing degree*, *Delay time*, *Sender_ID*, E_{rem}, $Cost_{sink \to s}$) packet and simply broadcasts it.

Step 2: Upon receiving the *RREQ* packet from upstream candidate *s*, node *s'* evaluates the front cost $C_{sink \to s'} = C_{sink \to s} + C_{s \to s'}$.

Step 3: If ($C_{sink \to s'} < C_{lowest}$), $C_{lowest} = C_{sink \to s'}$,

Node *s'* records upstream node=*s*, sets $RREQ.C_{\,sink \to s} = C_{lowest}$ and broadcasts the *RREQ* packet.

Phase II: The Route Reply Phase:

Step 1: The coordinator selects the route with lowest cost, creates an *RREP*(*Sender_ID*, *Receiver_ID*, *Destination_ID*, *First route*, $C_{sink \to R}$, $C_{sink \to p}$, $C_{e \to f}$, $Hops_{rem}$, $F_{current}$) packet and broadcasts it.

Step 2: Upon receving the *RREP* packet, the current and optimistic nodes check whether or not *RREP.first* route = true. If it is the case, current node broadcasts the *RREP* packet. Otherwise, the optimistic node will treat *RREP* packet as *S-RREQ* packet and then goto the Route Sharing Phase.

Step 3: Upon receving the *RREP* packet, the sink node records the downstream node *ID*.

Phase III: The Route Sharing Phase

Step 1: Upon receving the *S-RREQ* packet from sensor node *p*, optimistic node *q* evaluates the cost from the sink to itself and branch costs by

$$C_{sink \to q} = C_{sink \to p} + C_{p \to q} \text{ and}$$

$$C_{e \to q} = C_{e \to f} + C_{p \to q}.$$

Step 2: If ($C_{sink \to q} < C_{sink \to R}$) and ($C_{sink \to q} < C_{lowest}$), $C_{lowest} = C_{sink \to q}$.

Optimistic node q sets *S-RREQ*.$C_{sink \to p}$ = C_{lowest}, *S-RREQ*.$C_{e \to f}$ = $C_{e \to q}$ and *S-RREQ*. Hop_{rem}--, and broadcasts the *S-RREQ* packet.

Step 3: Upon receving the *S-RREQ* packet, the existing forwarding node t compares the frequecies of the existing and current routes.

If ($F_{current} \leqq F_{existing}$)

If ($C_{sink \to t} < C_{sink \to R}$) and ($C_{sink \to t} < C_{lowest}$)

Node t plays the role of brach node candidate, fills *S-ACK.Join*=0, sets *S-ACK*.$C_{sink \to b}$ = $C_{sink \to t}$ and replies the *S-ACK*(*Branch_node_candidate_ID*, *Attached_node_candidate_ID*, $C_{sink \to b}$, $F_{existing}$, *Join*) to the current node.

End if

Else go to Step 5

Step 4: Upon receving the *S-ACK* packet, the current node will be the candidate of attached node and simultaneously forward the *S-ACK* message to the sink node. Afterwards, the current node goes to Step 8.

Step 5: The existing forwarding node t evaluates the route cost from the sink to current node $C_{sink \to f} = C_{sink \to t} + C_{e \to f}$.

Step 6: If ($C_{sink \to f} < C_{sink \to R}$) and ($C_{sink \to f} < C_{lowest}$), the existing forwarding node t will be the candidate of the attached node, fill *S-ACK.Join*=1, sets *S-ACK*.$C_{sink \to b}$ = $C_{sink \to f}$ and then reply the *S-ACK* to the current node.

Step 7: Upon receving the *S-ACK* packet, the current node will be the candidate of branch node and simultaneously forward the *S-ACK* message to the sink node.

Step 8: The sink node will determine the best attached and branch nodes from all possible candidates and notify them and the coordinator to construct the shared route.

5 Simulations

This section evaluates the efficiency of the proposed DRSP. The proposed *DRSP* mechanism was implemented in GloMoSim (Zeng et al., 1998) and was compared with two mechanisms: *SAFE* (Kim et al., 2004) and Flooding. In the simulation, the sink nodes and sensor nodes are randomly deployed in the monitoring region with size 2000×2000 m^2. The number of sensor nodes is varied ranging from 300 to 500 and the number of sink nodes varies ranging from 1 to 10. A sensor node is chosen to play the role of coordinator, which is responsible to collect and transmit data to multiple sink nodes according to each sink node's query. Sensor nodes and sink nodes know their own location, and all sink nodes are also aware of the location of the coordinator. The common communication range of sink node and sensor node is 50 m. The energy consumption of sensor node for transmitting and receiving a packet is 1 and 0.5 μJ/bit (Kim et al., 2004), respectively. Table 2 summarises the parameters set in the simulation.

Table 2 Simulation setting

Parameter	*Value*
Simulator	GloMoSim
Node deployment	Random
Monitor Region	2000×2000 m^2
The number of sensor node	300~500
The number of sink node	1~10
Location information	Known
The communication range of sensor node	50 m
The energy consumption of transmitting	1 μJ/bit
The energy consumption of receiving	0.5 μJ/bit
The size of query packet	36 bytes
The size of data packet	64 bytes

Each sink node will separately construct the route with the coordinator in order. The coordinator will periodically transmit collected data based on the data attributes and returning frequency of requested from sink node. The sizes of query and data packets are set at 36 and 64 bytes, respectively. Each result is obtained from an average of 10 experiments. The 95% confidence interval is always smaller than ±5% of the reported values.

Figure 12 discusses the relationship between the number of sink nodes and the average number of sharing route. The number of deployed sensors is set at 500. In general, the average numbers of sharing routes constructed by *DRSP* and *SAFE* increase with the number of sink nodes. The *DRSP* and *SAFE* have similar performance and significantly outperform the Flooding mechanism in terms of the average number of shared routes. For instance, when the numbers of sink node in the network are 5 and 10, *DRSP* constructs 4.21 and 8.678 sharing routes, respectively, while *SAFE* constructs 4.35 and 8.783 sharing routes, respectively. The main reason that *SAFE* constructs more shared routes than *DRSP* is that *SAFE* uses flooding approach to build sharing route. Thus, *SAFE* exploits more opportunities for finding the sharing route than *DRSP*. The Flooding scheme builds route from each sink node to the coordinator by applying flooding operations, but the construction of sharing route is never considered. Therefore, the possibility of generating sharing route increases with the number of sink nodes.

Figures 13 and 14 investigate the control overheads and the number of forwarding nodes of the compared mechanisms, respectively. There are totally three sink nodes and 500 sensor nodes deployed in the monitoring region. Figure 13 compares the number of control packets of the three compared mechanisms with share degree ranging from 0 to 7. The numbers of control packets of *SAFE* and Flooding mechanisms keep a constant even though the requirements for share degree are changed. This is because that both *SAFE* and Flooding mechanisms perform flooding operations over the network, regardless of the requirement of share degree. The number of control packets created by the proposed *DRSP* increases with the requested share degree. When the value of the required share degree is larger than 5, the number of control packets created by *DRSP* would not change drastically. The main reason is that all sensors in the network help to broadcast the control packets in case that the required share degree is larger than 5.

Figure 12 The relationship between the number of sink nodes and the average number of sharing routes (see online version for colours)

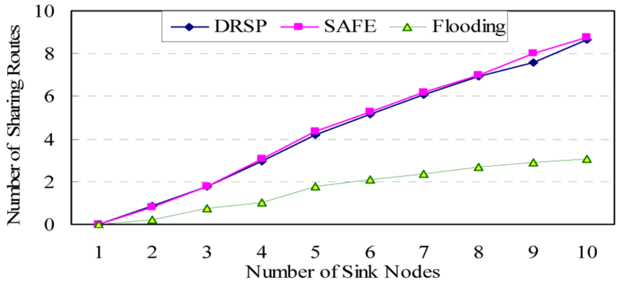


Figure 13 The relationship of share degree and control packet (see online version for colours)

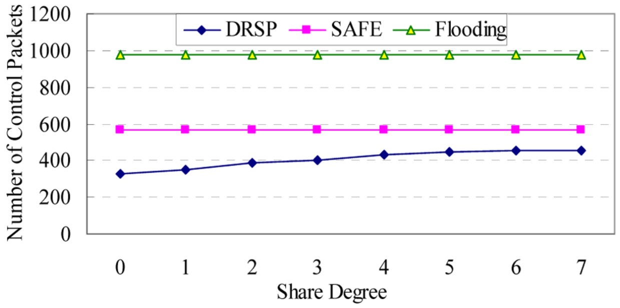


Figure 14 The relationship between share degree and the number of forwarding nodes on sharing route (see online version for colours)

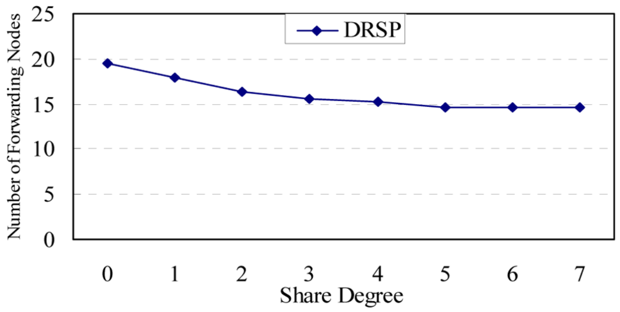
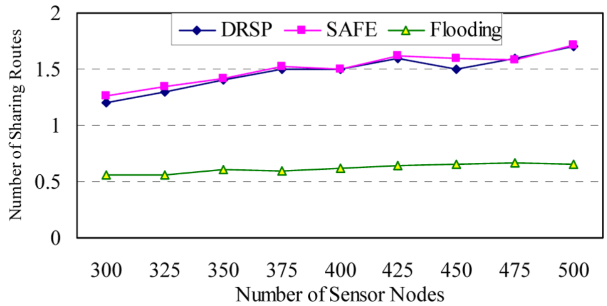


Figure 14 investigates performance comparison of the proposed *DRSP* in terms of the number of forwarding nodes lying on the shared route with various requested share degrees. In general, the number of forwarding nodes decreases with the required share degree. However, when the share degree is larger than or equal to 5, the number of forwarding nodes keeps a constant value. Therefore, the optimal share degree required for reducing the number of forwarding node is 5. In the following simulation, experiments will be undertaken under the environment where the share degree is set at 5.

Figure 15 compares the proposed *DRSP*, *SAFE* and flooding mechanisms in terms of the number of sharing routes with various number of sensor nodes. Three sink nodes with share degree 5 are deployed in the network. Here, the influence of different numbers of sensor nodes to the sharing route is compared. From the figure, it can be found that the number of sharing route increases with the number of deployed sensor nodes in the network, and performances of *DRSP* and *SAFE* are quite close, but the number of sharing route in *SAFE* is higher than *DRSP* without restraints of share degree.

Figure 15 The relationship between the number of sink node and the average number of sharing route (see online version for colours)



Moreover, two factors, including average energy consumption and control overhead, are also considered. In average energy consumption, the average power dissipation in route construction and data dissemination are mainly considered. In control overhead, the necessary control packet, which is issued in route construction, is considered. The dissipated power of each sink node and coordinator is shown as Figure 16. It can be found that *DRSP* dissipates less power than *SAFE* and Flooding. The main reason is that *DRSP* uses flooding approaches in local area, reducing the redundant control packets flooded over the network. Figure 17 depicts that *DRSP* consumes less power than *SAFE* and Flooding. The main reason is that when *DRSP* builds sharing route, it will adjust sharing route to the optimal sharing route based on the requested data attributes and returning frequency of sink node. Therefore, *DRSP* consumes less power than *SAFE,* which applies greedy algorithm to build route.

Figure 16 The power dissipation in route construction (see online version for colours)

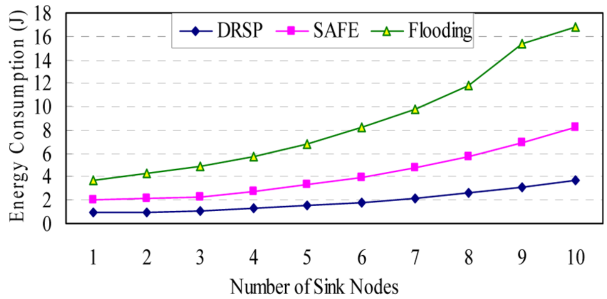


Figure 17 The power dissipation in data dissemination (see online version for colours)

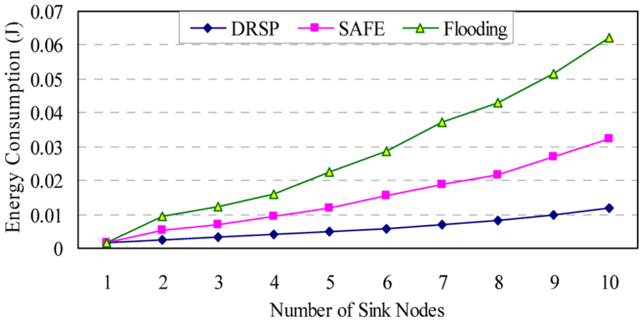
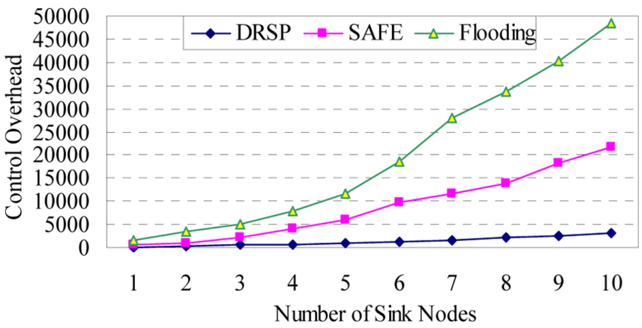


Figure 18 shows the overhead of building route between sink node and coordinator. It can be easily found that *DRSP* uses local flooding approach to find routes and its control overhead is roughly 3020 when there are 10 sink nodes in the network. But, the control overhead of *SAFE* and *Flooding* are 21785 and 48289, respectively.

Figure 18 The relationship between the number of sink node and control overhead (see online version for colours)



6 Conclusion

In the paper, a protocol that builds sharing route between multiple sink nodes and coordinator is proposed. The construction of sharing route can significantly reduce the number of forwarding nodes, the bandwidth waste and transmission of replicate data, achieving the goal of power saving. When the sink node requests data similar to the other sink nodes, the proposed *DRSP* tries to create a sharing route, and dynamically adjust the route according to requested attribute and returning frequency. Simulation results reveal that *DRSP* outperforms the existing schemes *SAFE* and *Flooding* and saves considerable energy consumptions.

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