國立交通大學

資訊科學與工程研究所

碩 士 論 文

於無線隨意網路中佈建路徑感知之移動節點進行資料重新導向

Route-Aware Mobile Relay Deployment for Traffic Redirection in a Wireless Ad Hoc Network

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摘　　要

近年來，相當多無線隨意網路相關的研究議題專注在利用可控制移動節點做為網路中的資料導向裝置以提升網路效能。 本篇論文的研究在混合式的無線隨意網路環境下提出一個資料重新導向的設計架構；考慮網路中存在一般的靜止節點，透過加入有限個數且電量較為充足的可控制移動節點，幫助原有的資料流量路徑以移動節點作為捷徑進行適當的資料重新導向。 本篇研究的主要目標在於：透過移動節點進行資料重新導向的幫助下，減輕網路中所有靜止節點總電量的消耗代價， 我們將此問題定義為移動節點佈建問題，並設計出一個分散式資料重新導向協定； 在我們的分散式協定中，移動節點將主動收集網路上的資料流量路徑資訊，計算出最佳的移動路徑， 並與靜止節點協同合作進行資料重新導向的動作。 最後，我們以QualNet模擬器對於網路效能做各項指標的評估，模擬結果顯示我們提出的資料重新導向協定能幫助網路環境在 不影響網路流量的前提下顯著的降低電量消耗。

關鍵字： 控制移動性，無線隨意網路，轉送節點佈建，省電，資料重導。

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ABSTRACT

Recently, many researches in wireless ad hoc networks focus on using mobility on controllable nodes to serve as special roles such as relay nodes to help improve the network performance. This paper considers a hybrid wireless ad hoc network and proposes a redirection scheme such that static network nodes can utilize limited number of mobile nodes ,which are resource-rich, as shortcut nodes of existing active flow paths for relaying traffics. Our goal is to mitigate the total energy costs consumed by static nodes with the assistance of mobile nodes. We refer to this problem as the mobile relay deployment problem and develop a novel distributed redirection protocol that mobile nodes actively collect the underlying routing information, optimally define their movements, and cooperate with static nodes in redirecting traffics. Finally, performances with different metrics are evaluated via QualNet simulations, and the simulation results indicate that the proposed protocol results in significant total energy reductions with comparable throughput under variant network environments.

Keywords: Controlled mobility, Wireless Ad hoc Network, Relay deployment, Energy Saving, Flow Redirection.

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國立交通大學資訊科學與工程研究所

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Chapter 1

Introduction

A wireless ad hoc network is a decentralized wireless network that communications occur between any pair of nodes in the absence of any preexisting infrastructure. In such network environments, each node not only operates as a host but also participates in the route discovery process of an ad hoc routing protocol and forwards packets for other nodes in the network that may not communicate directly within the transmission range of each other. Besides, the tasks performed by each node are variant and without fixed schedules, so the traffic pattern and the topology of a ad hoc network may change dynamically.

Recently, controlled mobility on nodes has been proposed as a possible solution that these nodes can act as special roles such as relay nodes to help the network prolong the lifetime. The movement of these relay nodes can be controlled by the underlying protocol to help the network improve the performance with specific objectives. Such mobility-aided system can be applied in several realistic scenarios. Consider a scenario of a wireless ad hoc network constructed in a disaster area. In such area, rescue teams may be dispatched to different small regions for searching survivors and set up communication stations, and some first-aid stations may be established for treatment. These communication systems form a temporarily wireless ad hoc network which is shown in Fig. 1.1. During the period of rescue, multi-hop communications may occur between any source-destination pairs such as one rescue team communicates to the other team in separate regions or seeks adjacent first-aid stations for support. We can deploy a limited number of mobile robots, which have rich energy or can be charged easily, to serve as guards moving around the disaster area. When the robots detect any active traffic within their communication range during the patrol, they can help relay the signals between the communication pairs. In such mobility-aided system, the total energy consumption of the network nodes can be reduced by the assistance of these relay nodes and therefore the working time of the communication devices are extended.

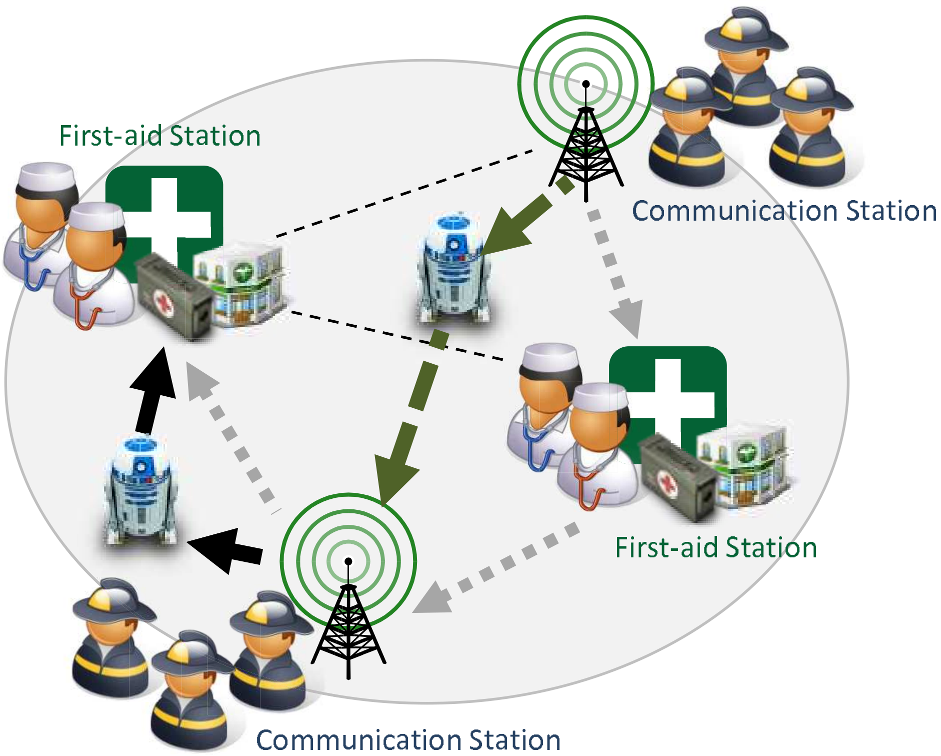


Figure 1.1: A mobility-aided system for a disaster area.

In [11], Venkateswaran et al. proposed a relay deployment framework under the environment of an ad hoc network which explores the possibility of using controllable relay nodes to relay the active single-hop flows within its neighborhood, and thus minimizes the energy consumption for transmission in the network. It considers a controllable transmission power scheme for each node in the network since a node consumes much more power in transmitting packets than in the packet reception and idle periods [2]. In their scheme, the sender nodes uti-

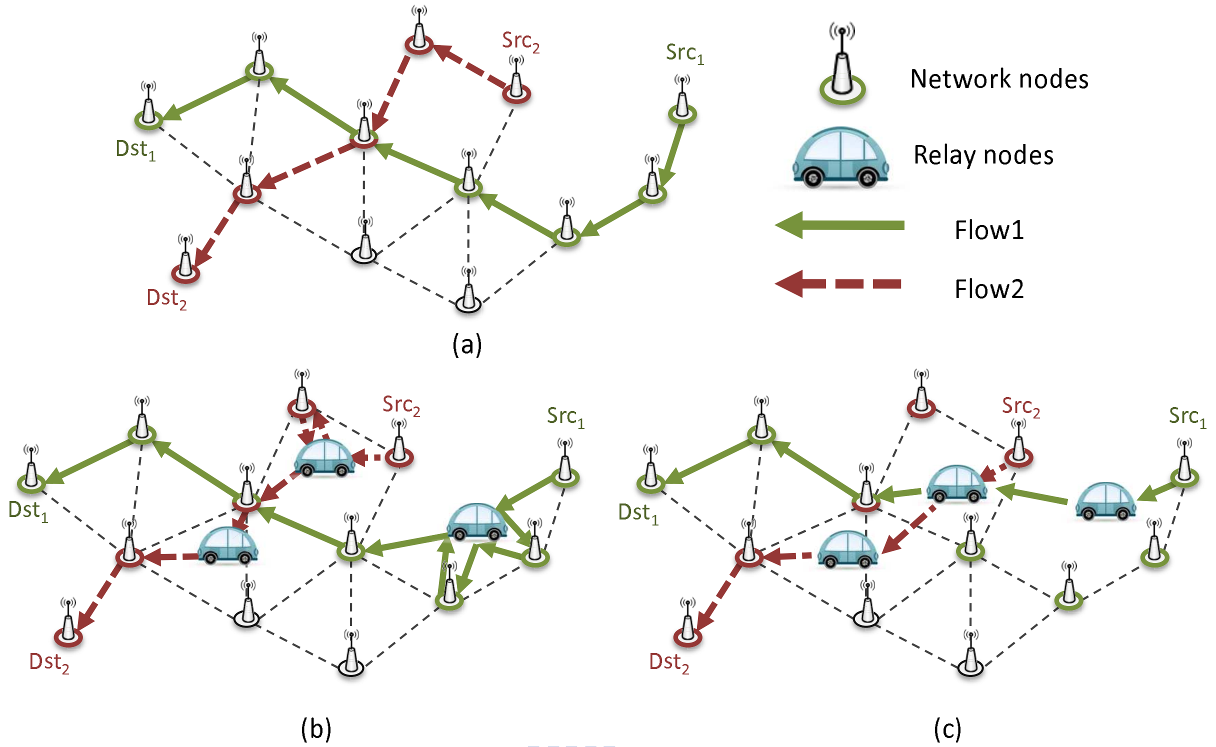


Figure 1.2: Different relay deployment schemes: (a) Original flow paths. (b) Flow paths redirected by relay nodes in link level. (c) Flow paths redirected by relay nodes in route level.

lize the relay nodes as intermediate nodes to transmit data if the distances between the senders and the relays are shorter than the original distances of the links, hence the transmission energies can be reduced. However, the design of [11] only considers the active flows in the link level; that is, a multihop flow is decomposed as a sequence of one-hop flows along the multihop path and ignores the routing information on the path to solve the problem.

In this paper, we present a new scheme that exploits the underlying routing information for relaying traffics, and thus works more efficient. We also consider a controllable transmission power scheme to dynamically adjust power between the transmission pairs. The basic idea behind the proposed scheme is to let relay nodes initiatively collect the underlying routing information, detect the active multihop end-to-end flows in the network environment and relocate to the optimal locations such that non-relay nodes can utilize them as shortcuts of original routing paths for communication. Fig. 1.2 shows a clear difference between link level and route level scheme. In Fig. 1.2 (a), There are two original multihop flow paths in the network without deploying any relay nodes. In the view of link level, every one-hop flow is seen as independent communication pair, so some successive one-hop transmissions in these flow paths are aided by the relay nodes in Fig. 1.2 (b). In contrast, two flow paths are both shortened in Fig. 1.2 (c) since the underlying routing information has been considered and therefore the total transmission energy cost is significantly reduced. To sum up, our goal is to shorten the routing path of the existing multihop flow paths by the assistance of relay nodes rather than finding new routes for the flows, and the extended network lifetime can be achieved since the total transmission energy is minimized by the optimized routes.

The rest of this paper is organized as follows. We discuss the related works in Section 2 and formally define the mobile relay deployment problem and the objective function in Section 3. We present a distributed protocol to the proposed problem in Section 4 and extend the protocol under the consideration of a fully mobile environment. Section 5 evaluates the performance through simulation results, and Section 6 concludes the paper.

Chapter 2

Related Works

Many existing works consider conserving transmission energy as the objective to design the protocols such as power-aware routing with different energy concerns [3][8]. In [3], the authors consider a dynamic power controlled routing scheme. The proposed routing protocol use more intermediate nodes to redirect the original one hop transmission and thus reduce the overall transmission energy consumption. [8] proposed a greedy localized strategy that source node (or intermediate node) selects one of its neighbor to forward packets with minimum total transmission power to the destination node. Most of these works joint the concept of redirection by network nodes to the routing algorithms. Variety of issues about power-aware routing protocols in ad hoc network have been surveyed in [4].

Most researches work on utilizing special devices with mobility such as mobile collectors [5][7][14] or mobile relays [12][13] to help lessen the overhead on relaying data along the routing path to the sink in static wireless sensor networks. In [5][7][14], mobile collectors move through the elected points with predefined trajectory to collect data from static sensors in single hop transmissions. [12][13] investigate a heterogeneous sensor network composed of a few mobile relays and static nodes. The authors proposed a joint mobility and routing algorithm that uses mobile nodes to help relay traffics from static nodes and thus improve the network lifetime. However, most of these works are designed for the unique traffic pattern in wireless sensor network (i.e. all traffics in the network will aggregate to the sink), and may not suitable to a general traffic pattern. Some of these approaches pre-plan the trajectories of mobile nodes; hence, they cannot handle the dynamics in the network environment.

Controlled mobility has been exploited to optimize energy consumption under the environment of wireless ad hoc network as well. In [9], the authors proposed a mobility controlled framework that relocates the network nodes to form an optimal routing path of a existing flow with two objectives: minimize total communication energy consumption and maximize network lifetime. The presented approach considers the energy cost on both communication and node movement for mobility decision making. However, the redirection scheme proposed in this paper is different from [9] since we consider a hybrid network consist of resource-rich mobile nodes to leverage the transmission overhead on simple network nodes. Further, our framework aim to not modify the underlying routing path of existing flows and ensure that the original routing mechanism can still work after mobile nodes stop serving.

Chapter 3

Mobile Relay Deployment Problem

We consider a hybrid ad hoc network with a collection of static nodes and some energy-rich mobile nodes. The main function of these mobile nodes is to serve as relays to forward those static nodes' traffics so as to lengthen the network lifetime. We refer to the problem of determining the locations of the mobile nodes the *Mobile Relay Deployment (MRD)* Problem.

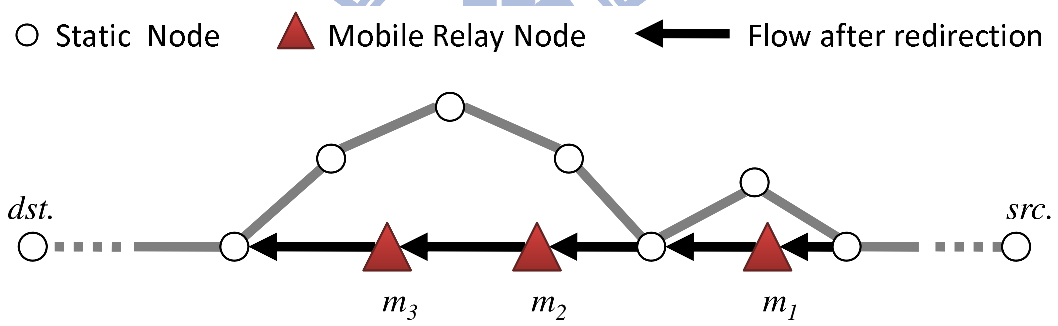


Figure 3.1: Some scenarios of using mobile nodes to help relay a flow's traffic.

Specifically, we are given an ad hoc network with a set N_S of static nodes and a set N_M of mobile nodes. The mobility of N_M is controllable. Nodes all have the same transmission distance and are all equipped with GPS receivers, so their locations are always known. Traffics are only generated by static nodes. Let F be a set of multi-hop flows among nodes in N_S. Each flow $\phi_i \in F$ is a sequence of nodes in N_S between a source-destination pair associated with a data rate λ_i. For any two static nodes n_j, $n_k \in \phi_i$, n_j is called n_k's *predecessor* if n_j is the immediate upstream node of n_k in ϕ_i, denoted by $pre(n_k)$. The main function of N_M is to relay the traffics of flows in F, whenever possible, to reduce energy consumption of N_S. Specifically, consider any multi-hop flow $\phi_j = (n_1, n_2, \ldots, n_k)$. Suppose that a mobile node $m \in N_M$ is moved within the transmission ranges of n_i and $n_{i+2} \in \phi_j$. Then we can replace $n_{i+1} \in \phi_j$ by m and redirect flow ϕ_j by a new flow $\phi'_j = (n_1, n_2, \ldots, n_i, m, n_{i+2}, \ldots, n_k)$. Note that the location of m is not necessarily the same as the location of n_{i+1}. It is also possible to use more than one mobile node collaboratively to redirect a flow. Fig. 3.1 shows two examples.

We assume that nodes of N_M are much more energy-rich, so we will only focus on the energy consumption of N_S. To model the energy-saving factor, suppose that (n_i, n_{i+1}) is a wireless link of a flow $\phi_j \in F$ such that n_i is the transmitter and n_{i+1} is the receiver. The transmit cost of n_i with respect to link (n_i, n_{i+1}) of ϕ_j is written as $E_t(\lambda_j, n_i, n_{i+1}) = \lambda_j \cdot e_t(d_{n_i,n_{i+1}})$, where $e_t(d_{n_i,n_{i+1}})$ is the transmit energy function. The energy function e_t is given by $e_t(d_{n_i,n_{i+1}}) = a + b \cdot (d_{n_i,n_{i+1}})^\alpha$, where $d_{n_i,n_{i+1}}$ is the distance between n_i and n_{i+1}, and a, b and α are environment-related constants (normally $\alpha \geq 2$) [8]. On the other hand, the receive cost of n_{i+1} with respect to (n_i, n_{i+1}) of ϕ_j is written as $E_r(\lambda_j, n_i, n_{i+1}) = \lambda_j \cdot e_r$, where e_r is the receive energy coefficient. Note that since E_t is distant-dependent, the location of mobile nodes would affect the transmit costs of static nodes.

Given N_S, N_M, and F, our goal is to determine the locations of mobile nodes in N_M to redirect as much traffics of F as possible to save static nodes' energies. We define the *Mobile Relay Deployment (MRD)* Problem as an optimization problem. Let F' be the new set of flows after redirection (note that sources and destinations of flows cannot be changed). The original energy cost of F can be written as

$$E(F) = \sum_{\forall \phi_j \in F} \sum_{\substack{(n_i, n_{i+1}) \\ \in \phi_j}} \left(E_t(\lambda_j, n_i, n_{i+1}) + E_r(\lambda_j, n_i, n_{i+1})\right) \tag{3.1}$$

On the contrary, for F', we only include the costs incurred on N_S, so we have

$$E(F') = \sum_{\forall \phi'_j \in F'} \sum_{\substack{(n_i, n_{i+1}) \\ \in \phi'_j}} (b(n_i, N_S) \cdot E_t(\lambda_j, n_i, n_{i+1}) \\ + b(n_{i+1}, N_S) \cdot E_r(\lambda_j, n_i, n_{i+1})), \tag{3.2}$$

where $b(x, N_S)$ is a binary function which returns 1 if node $x \in N_S$, and 0 otherwise (this is to exclude the cost on N_M). The *Maximum Reduction MRD (MR-MRD)* problem is to find the flow set F' such that $E(F) - E(F')$ is maximized.

Chapter 4

A Distributed Protocol for the MR-MRD problem

In this section, we propose a distributed protocol for the MR-MRD problem that would work in tandem with the underlying routing protocol adopted by the static nodes. Our protocol has two concurrent operations: *overhearing* and *serving*. The overhearing operation is for mobile nodes to collect the routing information in the network. The serving operation, which loops in three states, is to repeatedly relocate mobile nodes to better locations and to help redirect static nodes' flows. Fig. 4.1 shows the overall operations. More details are given in the subsequent sections.

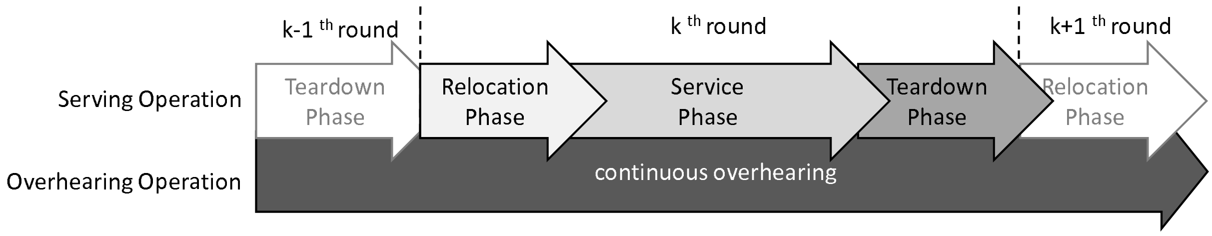


Figure 4.1: Two simultaneous operations: overhearing and serving.

4.1 Overhearing Operation

In order to find out the opportunity for traffic redirection, each mobile node actively overhears packets sent by its neighboring static nodes. Form the collected information, a *Flow Table* is maintained, which will help find shortcuts in the serving operation. The table will contain both active and idle flows passing through. In the following, we assume that static nodes adopt *Ad-hoc On Demand Distance Vector Routing (AODV)* [6] as their underlying routing protocol.

In *AODV*, the path discovery process will issue *Route Request (RREQ)* to search for routes to intended destinations and *Route Reply (RREP)* to confirm selected routes. Also, when a route is found to be broken , *Route Error (RERR)* will be sent along the segmented routes to report the breakage. Each entry in a Flow Table has the format $(N_{target}, N_{from}, C_{hop}, C_{pkt}, B_{pkt}, \tau_{pkt})$, where N_{target} is an end node that a flow is connected to, N_{from} is a static node on the flow neighboring to the mobile nodes, C_{hop} is the hop count from N_{from} to N_{target}, and C_{pkt} is the number of packets sent by N_{from} for the flow recently; The last two columns, B_{pkt} and T_{pkt} are used to estimate the data rate for the flow to N_{target}, where B_{pkt} is the accumulated packet size and T_{pkt} is the first packet arrival time. The Flow Table is indexed by (N_{target}, N_{from}). For example, Fig. 4.2 shows a mobile node M with a flow from S to D passing through. Table 4.1 shows that seven entries are maintained for this flow by M. Below, we discuss how a mobile node M_i maintains its Flow Table when overhearing a RREQ/RREP/RERR packet and a data packet:

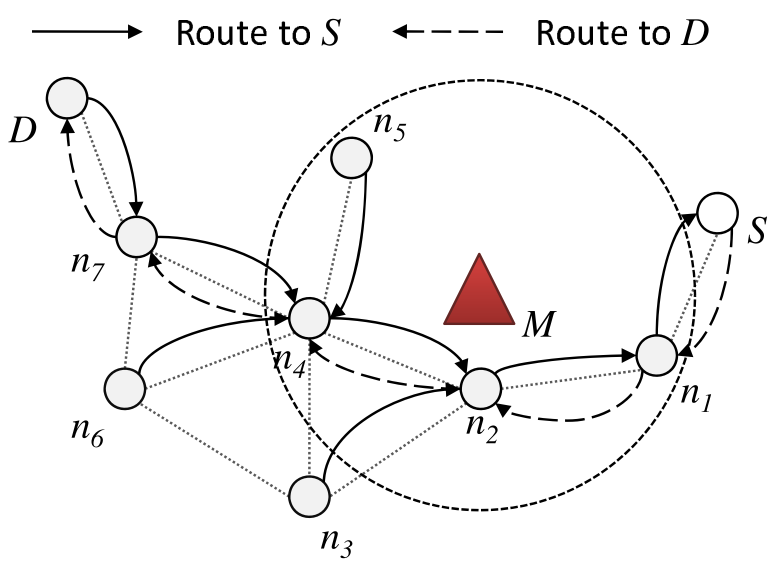


Figure 4.2: Established routes for the multi-hop flow from S to D.

Table 4.1: Flow table maintained by M in the overhearing operation.

N_{target}	N_{from}	C_{hop}	C_{pkt}	B_{pkt}	τ_{pkt}
D	n_1	4	c_i	b_i	τ_i
D	n_2	3	c_j	b_j	τ_j
D	n_4	2	c_k	b_k	τ_k
S	n_5	4	0	0	0
S	n_4	3	0	0	0
S	n_2	2	0	0	0
S	n_1	1	0	0	0

1. RREQ: A static node S_i broadcasts a RREQ in the path discovery process of a multihop flow (Src, Dst) indicates that it's exactly Src or it's an intermediate node on the route to Src, and the hop distance h_i from S_i to Src is contained in RREQ. When M_i overhears the RREQ from S_i, it inserts an entry $(Src, S_i, h_i, 0, 0, 0)$ for the reverse route to Src with S_i as the next hop. Duplicated RREQ from S_i to Src will be used to update h_i.

2. RREP: A static node S_i may unicast a RREP to notify the source Src that a route has been found to the destination Dst or it's exactly Dst, and contains the hop distance h_i from S_i to Dst in RREP. When M_i overhears a RREP from S_i, it inserts an entry $(Dst, S_i, h_i, 0, 0, 0)$ for the forward route to Dst with S_i as the next hop. Duplicated RREP from S_i to Dst will be used to update h_i.

3. RERR: A static node S_i issues RERR to the previous hop of the route to the destination Dst for reporting that the broken next hop S_b to Dst is detected in its neighborhood. When M_i overhears a RERR from S_i, it simply invalidates the entries with Dst as N_{target} and S_b as N_{from}.

4. Data packet: When M_i overhears a data packet from a static node S_i for the flow to the destination Dst , it increases the C_{pkt} of the entry indexed by (Dst, S_i) and accumulates the corresponding B_{pkt}. τ_{pkt} is set if the data packet is overheard for the first time. For evaluating the stability of a flow, we apply an aging process by decreasing C_{pkt} once

every time interval ΔT so that the accumulation of C_{pkt} will be affected by time. M_i resets C_{pkt}, B_{pkt} and τ_{pkt} once every serving operation.

The management policy of the Flow Table in mobile nodes follows the cache mechanism in AODV and thus the routing information maintained in mobile nodes can be up-to-date. Based on the collected information in Flow Table, each mobile node can utilize the entries with the same N_{target} but different (N_{from}, C_{hop}) to find a redirection opportunity for a stable route to N_{target} whose stability is evaluated by C_{pkt} among these entries, and serve as intermediate node to redirect the flow traffics toward N_{target}.

4.2 Serving Operation

The serving operation of a mobile node M_i is divided into rounds. Each round has three phases: relocation, service and teardown. In the relocation phase, M_i will collect active flows from its Flow Table and compute the location where it should move to. In the service phase, M_i will actively notify the static nodes it should served, start redirecting traffic from these nodes and relocate to the location which is computed in the previous phase. In the teardown phase, M_i will terminate failed redirections when detecting any link breakage.

4.2.1 Relocation Phase

In the first phase, M_i will detect the active flows by checking the Flow Table maintained by the overhearing operation and finds out redirection opportunities. A flow is seen to be active if some static nodes on the route which pass through M_i's neighborhood are enough stable for transmission. This can be done by checking C_{pkt} of each entry in the Flow Table. We explain the relocation phase in detail as follows.

First, M_i skip the entries in the Flow Table if the value of $C_{pkt} < \Delta S$, where ΔS is a threshold value for testifying the stability of the transmission from N_{from}. Then, for each Dst_k

in N_{target}, M_i checks the entries $(Dst_k, N_i, h_i, c_i, b_i, \tau_i)$ to find out redirection opportunity for flows to Dst_k. If there exists two entries $(Dst_k, N_i^t, h_i^t, c_i^t, b_i^t, \tau_i^t)$ and $(Dst_k, N_i^r, h_i^r, c_i^r, b_i^r, \tau_i^r)$ that fulfils the following constraints: (1) N_i^t and N_i^r are both M_i's active neighbors, (2) $h_i^t > h_i^r$ and $(h_i^t - h_i^r)$ is maximized, then M_i successfully finds a shortcut for flows to Dst from N_i^t to N_i^r and relays the traffics by itself. The first constraint is to ensure that M_i can always service N_i^t and N_i^r in the period of the service phase since they are both within M_i's transmission range, while the second constraint is to ensure that the existence of the redirections shortens at least one hop from the original routing path and finds the maximum saving in terms of hop distance.

(N_i^t, N_i^r) is called a *redirect pair* of M_i for flows to Dst_k, and its data rate is estimated by b_i^t and τ_i^t. M_i maintains a *Service Table* which contains a redirect pair, and the data rate and the original transmission cost of serviced flow for each entry. Since M_i may not be able to communicate to all the nodes on the path of a flow, it's challenging to get the original energy cost of the subpath from N_i^t to N_i^r. Therefore, we use the transmission energy cost for full power times the shortened hop distance $(h_i^t - h_i^r)$ to approximate if $(h_i^t - h_i^r) \geq 2$. The construction of redirect pairs is a greedy choice since we only consider the maximum $(h_i^t - h_i^r)$ to find a redirect pair for each Dst_k and simplify the complexity for detecting and searching all subpaths.

After collecting a set of redirect pairs, a local view in M_i's one-hop neighborhood has been constructed which is given by (L_S, M_i, P) where $L_S = \{x | x \in N_S, x$ is M_i's one-hop neighbor$\}$, and P is all the redirect pairs associated with their properties in M_i's Service Table. The following operation is to determine the solution to MR-MRD by M_i under (L_S, M_i, P). We solve MR-MRD by dividing into two subproblems. First, we propose two feasible solutions under different considerations to select a set of candidate locations that mobile relays can relocate to. Then we solve MR-MRD based on the set of candidate locations.

There are two feasible solutions to select candidates from different perspectives. We can

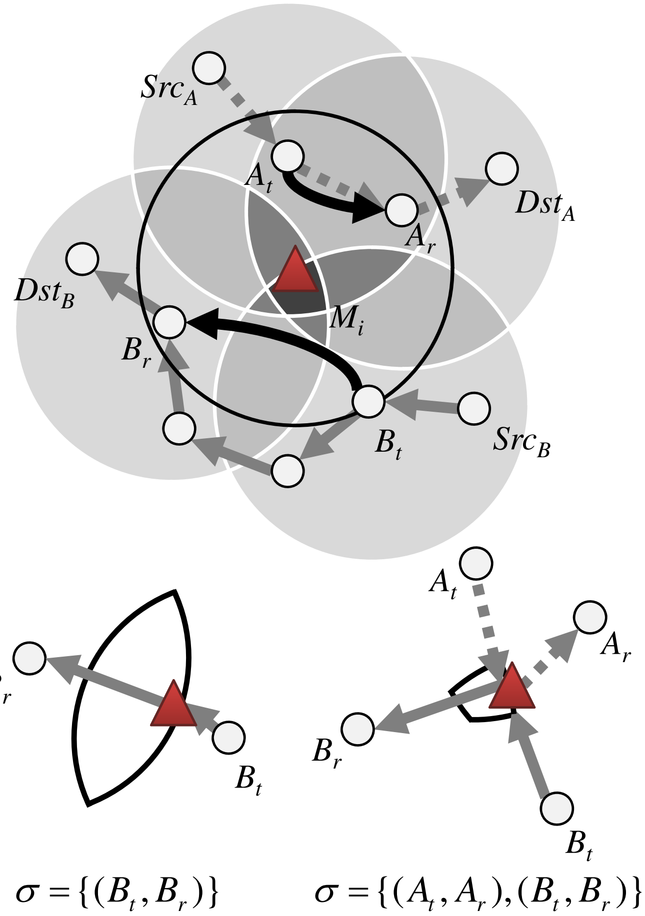


Figure 4.3: Examples of possible regions.

divide a specific field centered by M_i into several grid points and let the height and width of the grid be configurable parameters. In such a way, we can rapidly find a finite set of candidates which contains the locations of all the grid points. The advantage of finding grid points is simplicity and without complicated calculation. However, since it's an approximate method in the absence of considering network properties, the location for M_i chosen from the candidate set may not be optimal. In contrast to the grid approximation, the second method make a deeper observation for a local view. For a redirect pair $(S_t, S_r) \in P$, the possible region to locate M_i is the intersection area between the communication range of S_t and S_r. Therefore, each possible region can be represented by a set of redirect pairs. Fig. 4.3 shows some examples of possible regions with two redirect pairs in M_i's local view. Once we obtain a possible region σ associated with a set of redirect pairs $R_\sigma = \{(S_t^i, S_r^i)\}$ where $(S_t^i, S_r^i) \in P$, we can find an optimal location of M_i in σ that minimizes the transmission energy for redirection. Based on the energy function E_t mentioned in the previous section, the energy consumption for σ when deploying M_i on different locations in σ only affect the transmission energy costed by S_t^i since the energy for reception remains constant. The transmission energy cost can be formulated as

$$\sum_{(S_t^i, S_r^i) \in R_\sigma} E_t(\lambda_i, S_t^i, M_i) \tag{4.1}$$

To minimize Eq. (4.1), it can be proved that the optimal location of M should be the closest location in σ to the weighted geometric center G_σ of the locations of all S_t^i, where the weight of S_t^i is assigned to λ_i and the exponent α in E_t equals two. This optimal location can be exactly found by geometric relations between G_σ, the area of σ and the locations of S_t^i and S_r^i. We use the solution for $\alpha = 2$ as an approximation for scenarios where $\alpha > 2$. By enumerating all the possible regions, we can find out all possible ways to redirect flows and the corresponding optimal locations for M_i. It's the most precise way to list all the candidate locations. Since it's more complicated, this solution has higher complexity in calculation than the grid approximation.

After obtaining a set of candidates, we solve MR-MRD based on these locations as follows. Given a set C of candidate locations, we define $Reduction(c \in C)$ which returns the sum of the maximum reduction cost, a non-negative value, for each redirect pairs that M_i can serve at c. For example, if there exists a candidate c_x associated with a redirect set $\{(S_t^k, S_r^k)\}$, then $Reduction(c_x) = \Sigma[max(0, W_{tr}^k - E_t(\lambda^k, S_t^k, M_i))]$ where W_{tr}^k is the original cost of the flow from S_t^k to S_r^k. We choose the c_{max} which has the maximum $Reduction(c_{max})$ as the optimal location for relocating M_i with the corresponding optimal redirect pairs. M_i marks the entries of the optimal redirect pairs in the Service Table and starts to serve these pairs.

4.2.2 Service Phase

The service phase is used to start and process the redirection. We describe the operation in the service phase as follows. After mobile node M_i calculates the optimal redirect pairs $\{(S_t^i, S_r^i) \mid S_t^i, S_r^i \in N_S\}$ and the optimal location χ_{op} during Computation Slot as mentioned above, M_i initiates control messages, called *Redirect Request (ReREQ)*, to each S_t^i and schedules the next move to χ_{op}. The static node S_t^i which receives a ReREQ maintains a *soft state* in a *Relay Table* to keep the redirect information and automatically terminates when either the linkage between M_i and S_t^i breaks or the timer of the state expires. S_t^i can simply modify the source route of the received data packets to M_i if the soft state in the Relay Table exists and start redirecting. When M_i receives a data packet of a flow (S_{src}, S_{dst}) from $S_t^* \in S_t^i$, it simply looks up a marked entry which is indexed by (S_{src}, S_{dst}) in the Service Table, and then relays the packet to S_r^* according to the entry.

4.2.3 Teardown phase

In the teardown phase, mobile node M_i actively terminates the redirections by initiating control messages, called *Redirect Cancel (ReCAL)*, to the senders which are being involved in the redirection paths. The static node which receives a ReCAL expires the corresponding redirection soft state in the Relay Table and uses the original route as normal. Notice that, it is possible that links break (e.g. inactive S_r^i) during the service phase and the breakages cause packets drop due to failed redirections. Therefore, mobile nodes may send ReCal to the senders which are being involved in failed redirection paths before the teardown phase in such special situations.

Chapter 5

Simulation Results

In this section, we evaluate the performance of our proposed redirection schemes. We implemented the relay redirection framework in QualNet simulator [10]. We place network nodes by uniform random deployment in a $750m \times 750m$ 2D terrain. Each simulation run is simulated for 1 hour duration and each of the results presented in this section is averaged over thirty simulation runs.

We simulate the ad hoc network under IEEE 802.11b environment with a channel data rate of 2 Mbps and use 802.11 MAC protocol for wireless transmission through a free space path loss model. The maximum transmission power of each node was set to 6.633 dBm which corresponds to a transmission range of approximately 250 meters under a packet reception threshold of -91 dBm. We set the power consumption model in a similar way represented in [1] to simulate a realistic implementation of the network interface. There are three categories of end-to-end traffic flows in the network:

1. Four high-rate 120kbps UDP request traffic with 1 KB packet size.
2. Four medium-rate 40kbps UDP request traffic with 1 KB packet size.
3. Four low-rate 0.8kbps UDP request traffic with 100 byte packet size.

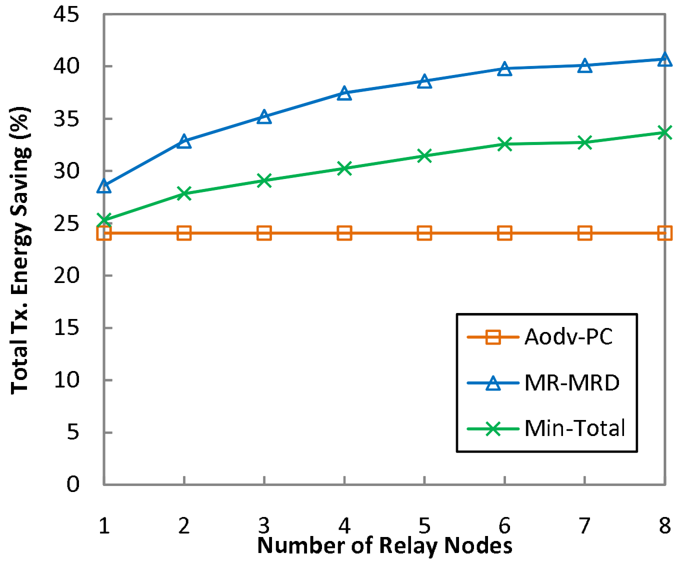
For each request from the source node, the destination node responses one reply packet with 512 byte packet size. All traffic flows are random source-destination pairs with random start times and durations. Besides, through the simulation, all static nodes in the network broadcast a *Beacon* message once every *Beacon Interval*. The beacon is used to exchange location information and preserve connectivity among neighbor nodes. These information can help static nodes to estimate the distances between neighbors at a specific time and to appropriately adjust their transmit power for communication. We let Beacon Interval be equal to the length of the service phase.

We compare our proposed protocol (denoted by 'MR-MRD') against the deployment framework with minimum total energy (denoted by 'Min-Total') proposed in [11] and use AODV as the underlying routing protocol in the simulation. The energy reduction in both MR-MRD and Min-Total can be divided into two parts. The first part is from the controllable power scheme which minimizes the total energy consumption by reduce the transmission power according to the distance between the communication pairs; the second part is due to the traffic redirection scheme by controlled mobile nodes. To quantify the part of total reduction by power control, we apply the controllable power scheme to AODV (denoted by 'Aodv-Pc') and without the assistance of any relay nodes as a comparison protocol. In our simulation results, we use the network environment, which is only composed of non-relay nodes and functions AODV (denoted by 'Aodv-Pure'), as a basis and design two metrics to evaluate the performance among different protocols as follows.

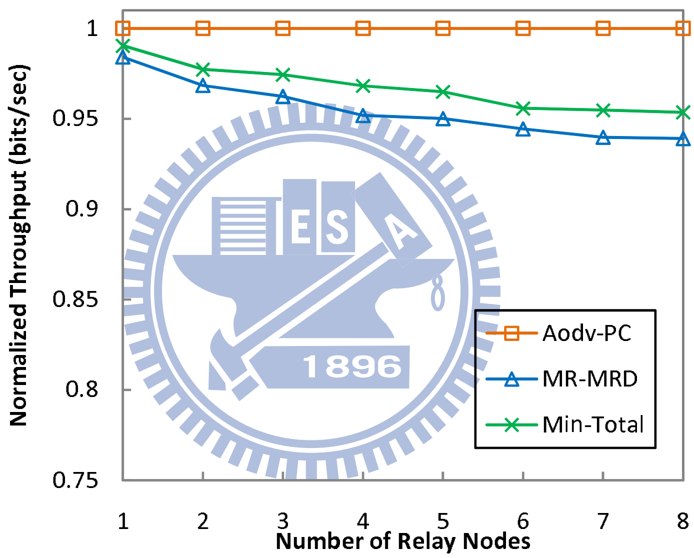
1. The total transmission energy saving: We measure the energy saving in the network as follows. Let E be the total transmission energy in Aodv-Pure and E_P denote the total energy consumed in transmission when the protocol P is applied. Then the energy saving in transmission is computed as $(E - E_P)/E$.

2. Normalized throughput: We measure the throughput of the traffic flows in a protocol and normalize the value by the throughput in Aodv-Pure.

In the first experiment, we observe the performance when varying number of mobile relay nodes. We fix the number of static nodes and the length of the service phase to 25 nodes and 15 seconds respectively. Fig. 5.1 (a) shows that power control scheme (i.e. Aodv-Pc) reduce about 24 percents of total transmission energy consumption. Our redirection scheme, which can improve the saving to about 28 to 40 percents, is much better than Min-Total. This result shows that redirecting in route level has more opportunities than in link level, and thus has better performance gain. However, the increasing number of additional relay nodes results in the increasing channel contention when a node start to transmit packets and decreases the channel utilization. Fig. 5.1 (b) shows that the network throughput decreases due to the assistance of additional relay nodes rather than power control in transmissions. Besides, when a route entry in the route table is used to transmit a data packet, its lifetime will be extended. The route-level redirection of flows in MR-MRD let some intermediate nodes be omitted in the new path and has less chance to update their entries. Thus, these entries expire quickly during the redirection. Note that route entries will always be updated in link-level redirection since data packets are only forward a single hop. This phenomenon results in more data packets dropped due to expired routes in MR-MRD than in Min-Total after relay nodes leave, and explains the performance gap between them.



(a)



(b)

Figure 5.1: Results with varying number of relay nodes in static networks. (a) Performance Improvement. (b) Throughput.

In the next experiment, we deploy 4 relay nodes and keep the length of the service phase in 15 seconds. We vary the network density by deploying different number of static nodes and compare the performance. In a sparse network, longer distance between nodes and their neighbors result in more energy consumed on some nodes in data transmissions, and thus the flow traffics relaying by additional relay nodes can significantly leverage the overhead of these static nodes, as can be seen in Fig. 5.2 (a). The networks with variety of density do not affect the occurrences of redirection since the hop distances of the routing paths selected by AODV remain stable through these networks, and result in a stable trend of throughput which is shown in Fig. 5.2 (b).

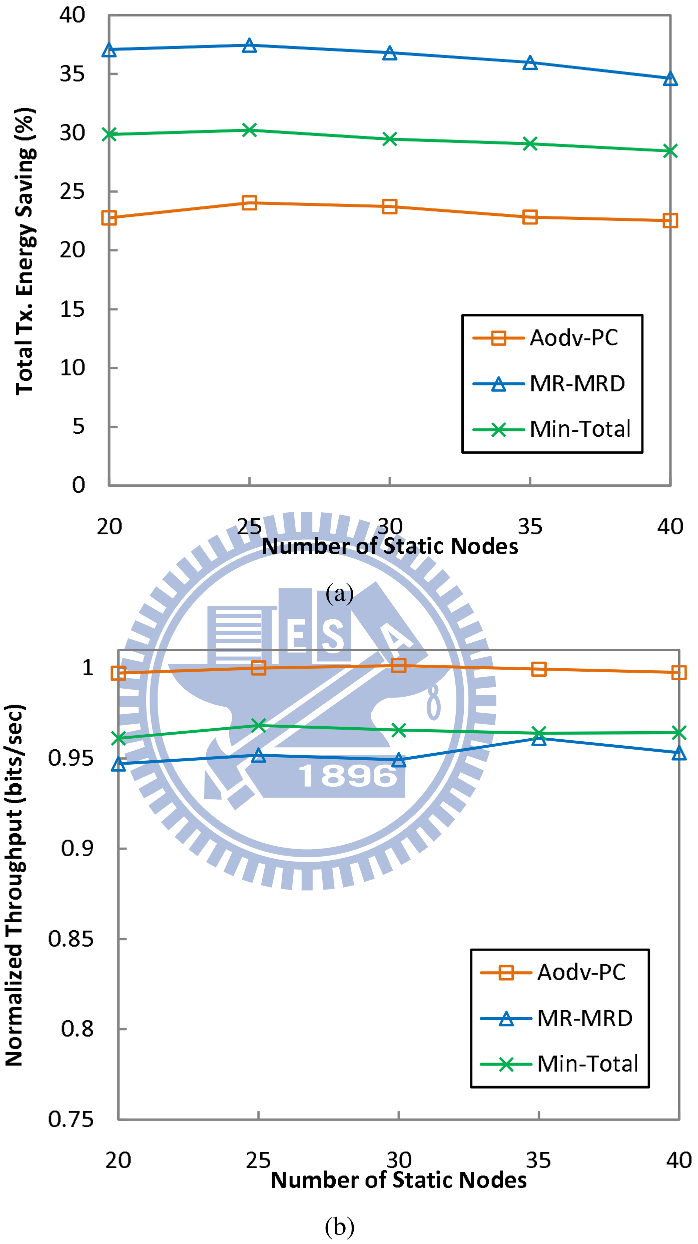
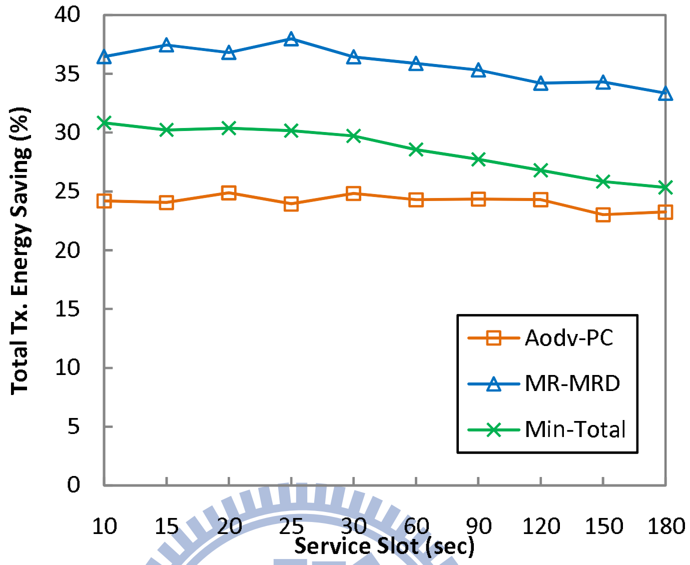
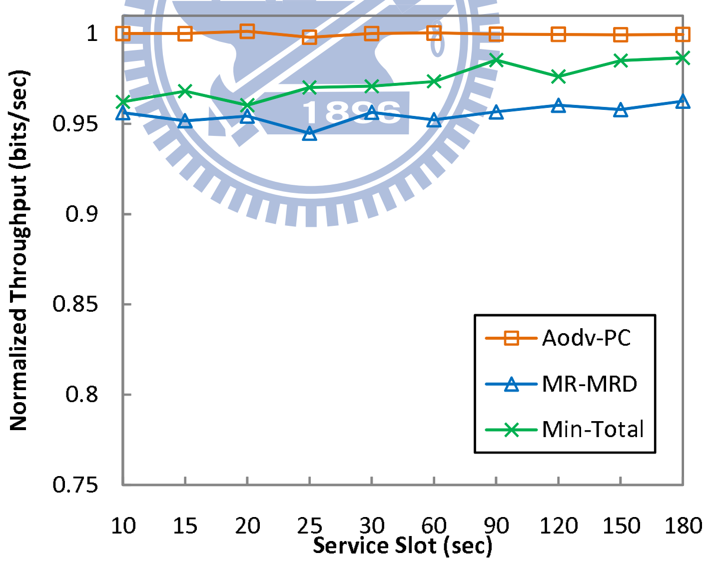


Figure 5.2: Results with varying network density in static networks. (a) Performance Improvement. (b) Throughput.

To observe the effect of different periods of service length, we deploy 25 static nodes and 4 mobile relay nodes, and vary the length of the service phase. Fig. 5.3 (a) shows that the traffic pattern of the network environment may be suitable for a particular setting of the service phase. Appropriate setting of the service phase can lead to a better traffic redirection; that is, mobile nodes will not stay in the neighborhood of flows with short durations, and wait for service even if the flows become inactive. Fewer redirections occur mitigate the control message overheads in the network, increase the channel utilization and thus increase the throughput of the network. Specifically, static nodes in Min-Total need to initiatively detect active flows and inform relay nodes about these information; therefore, Min-Total has more benefits from reduced control message overheads than MR-MRD in terms of throughput. Fig. 5.3 (b) shows the results for throughput.



(a)



(b)

Figure 5.3: Results with varying service length in static networks. (a) Performance Improvement. (b) Throughput.

Chapter 6

Conclusion

Energy-conserving is a critical issue in wireless ad hoc networks. We consider controlled mobility as a solution that some controllable resource-rich nodes can act as relay nodes to help network lessen the total energy costs. In this paper, we defined the mobile relay deployment problem that aims to minimize the energy consumption at static nodes with the assistance of relay nodes, and proposed a novel distributed protocol that utilizes underlying ad hoc protocol information to optimally shorten the routing paths of existing flows. The simulation results indicate that our protocol results in significant total energy reductions with comparable throughput under different network environments.

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Publication Lists

1. F.-J. Wu, H.-C. Hsu, Y.-C. Tseng, and C.-F. Huang, "Non-location-based Mobile Sensor Relocation in a Hybrid Static-Mobile Wireless Sensor Network", *In Proceedings of the 2009 Third international Conference on Sensor Technologies and Applications (SENSORCOMM' 09).*