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Routing in wireless/mobile ad-hoc networks via dynamic group construction

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An ad-hoc network is temporarily formed by a group of mobile hosts communicating over wireless channels without any fixed network interaction and centralized administration. When a mobile host communicates with other mobile hosts in an ad-hoc network, the routes are established via the intermediate mobile hosts as forwarding nodes. Under such a network environment an adaptive approach for routing management will be proposed in this paper. In this approach, at first the network infrastructure is constructed by several communication groups, which are called *routing groups*. A routing group communicates with other routing groups via the boundary mobile hosts as forwarding nodes. In a routing group the mobile hosts are divided, by means of the *dominating values,* into two groups – one *positive* cluster and several *non-positive* clusters. The nodes in the positive cluster maintain the topology information of the routing group. Under such a construction environment, intra-group routing performs unicasting and gets multiple paths, while inter-group routing performs on group level by propagating the route requests to the boundary clusters, which are called *bridge clusters*. This routing scheme massively reduces the message complexity that is especially important for system performance under such a resource constraint environment. As far as the dynamic topology characteristics of ad-hoc networks are concerned, this approach also provides a more efficient infrastructure update. Finally, simulation results show that the routing via dynamic group construction outperforms the previous works in message complexity and infrastructure update efficiency.

1. Introduction

Mobile communication and wireless networking are becoming more and more popular nowadays. The mobile communication environment is often integrated into traditional networks like the Internet or Intranet [8,11,12]. However there are base stations which directly keep track of the mobile hosts. The wireless communication only interacts between the mobile hosts and their access points on a fixed network. Although two mobile hosts are in the transmitting range of each other, they must communicate with each other by some base station.

Under some circumstances, the mobility support is not available. For example, the access points are not set up due to low cost effect, poor performance or low usage. This may occur in some situations, such as in outdoor conferences, emergency situations of natural disasters and military deploys in battlefield. Without the access points the mobile hosts under this environment must form an ad-hoc network.

An ad-hoc network is temporarily formed by a group of mobile hosts communicating over wireless channels without any fixed network interaction and centralized administration. In the infrastructure, all the mobile hosts communicate with other mobile hosts in a wireless multi-hop routing style. All the mobile hosts act as routers in the network. Because the routers are mobile, the network topology is changed frequently by some events among mobile hosts. For examples, the mobile hosts switch on/off or the mobile hosts move from some place to another. The routing scheme in ad-hoc networks is more challenging than traditional networks in terms of dynamic network topology. However, in ad-hoc networks the routing scheme is an important factor to improve the network efficiency.

Recently there have been some researches on routing in ad-hoc networks. Based on the traditional routing method, loosely source routing, D.B. Johnson et al. propose on-demand dynamic source routing [5–7,9,10,23] in ad-hoc networks. A mobile host propagates the route discovery message all over the network while a routing request is being issued. Each node that is forwarding this route discovery message adds its address into the source list. Finally the message reaches the destination node. The complete path from source to destination is listed in the packet. The route is replied to the source node. The routes discovered in this way or by hearing routing message in its neighborhood are recorded in the cache.

Another ad-hoc network routing approach is cluster-based philosophy. P. Krishna et al. propose that the ad-hoc network is clustered as a two-level network graph [13,14,22,24]; the upper level is the cluster-level connected graph, and the lower level is the origin node-level connected graph. At first it constructs overlapping clusters structure in the network. Each node should maintain not only intra-cluster topology information but also the inter-cluster topology. The traditional routing algorithms can be applied in the infrastructure.

Z.J. Haas et al. propose the zone routing scheme [18–20], which is somewhat similar to the cluster-based approach. For each mobile node it maintains all the links within the defined radius, the so-called “zone”. This maintained range for each node is alike to the cluster. When a route request is issued, it searches within the zone. Moreover, the inter-zone searching is executed by multicasting request message to its boundary nodes. The boundary nodes proceed with the same route searching strategy. Finally the route or failure message are replied.

Another approach [1,16] is proposed by B. Das et al. They use the characteristic of the minimum connected dominating set (MCDS) to construct a so-called virtual backbone in an ad-hoc network. All the nodes not in the virtual backbone have their dominators that are the access points on the virtual backbone. A mobile host communicating with other mobile hosts may be routed through the virtual backbone by its dominator. However, the maintenance of virtual backbones is the critical problem of this method. Besides, some other approaches perform routing schemes by means of auxiliary information, such as signal stability information [15] and location information [17].

In our approach, like the cluster-based and the minimum connected dominating set approach, there are two phases for the routing management in ad-hoc networks. Similar to graph theory, we call the mobile hosts as mobile nodes in ad-hoc networks. In the construction phase, a mobile node interacts with its nearby mobile nodes. Initially by comparing the information of connectivity with its neighbors, each mobile node determines itself whether it is a *positive* or a *non-positive* node. The determination is defined in section 2.2. After all the mobile nodes have been determined, the connected positive nodes will be simultaneously grouped as a positive cluster and the connected non-positive nodes as a non-positive cluster. The two types of constructed clusters are interleaved with each other in the ad-hoc network. The positive cluster plays the role of topology information center for its adjacent non-positive clusters. In the maintenance phase, some variations will affect the network topology. In order to retain the constructed structure for the network routing, there must be some appropriate processes reacting to these variations. Therefore, the constructed infrastructure of the ad-hoc network is dynamic. When a mobile node tends to communicate with other mobile nodes, at first it performs route searching in local topology information. When the routes are not found, it issues route searching to the nearby positive clusters. If the routes are still not yet found, it issues route searching through the whole network. Because of the maintenance of topology information in positive clusters, the traditional path searching algorithms can be applied in the domain of a positive cluster and its adjacent non-positive clusters; such a domain will be named a *routing group* in this paper. It is self-evident that routing groups are dynamic in ad-hoc networks. Routing in ad-hoc networks in our approach is by means of the routing group construction and maintenance.

2. Models and definitions of dynamic group routing

In this section, we will describe the ad-hoc network model and some definitions for routing via dynamic groups. Some terms are similar to the definitions of IETF Internet draft [4]; while some other terms are first defined in this paper. These definitions in the ad-hoc network environment will be applied to the dynamic group routing algorithms in section 3.

2.1. Ad-hoc network model

In an ad-hoc network, all the mobile nodes communicate with each other by wireless channels. A physical medium that can sustain data communication between two nodes is called a link. A link may be asymmetric between two nodes. The transmission characteristics of a link depend upon the relative position or design characteristics of the transmitter and the receiver on the link. Due to the property of asymmetric links, a node may receive a message from another node but its transmitting message cannot reach the transmitting one. Also, a link may be symmetric. Both of the two nodes can communicate with each other by local broadcast. If there is a symmetric link between two nodes, we call them neighbors of each other. On the other hand, we call them semi-neighbors of each other in the case of an asymmetric link between two nodes.

Since there are two types of links in ad-hoc networks, it is assumed that each node in the network can detect its neighbors and transmitting semi-neighbors by local broadcast. Each node will broadcast a beacon control signal in a time period so that it can detect the state of a link: "connected" or "disconnected" of a link. The control signal may communicate over the dedicated control channels. In our approach only the symmetry links are applied in constructing the *routing groups*.

In ad-hoc networks the message is routed in the multihop style along the links. All the mobile nodes act as routers. They are assumed to be willing to forward the message when forwarding request is made. There is no cheating along these intermediate nodes when a message is forwarding. However, the nodes are mobile. The network topology constructed by links is also dynamic in ad-hoc networks.

2.2. Definitions in dynamic routing group

Initially we describe some denotations in this section. For a mobile node p in ad-hoc networks, deg(p) is the degree of this node. In other words, the node p has deg(p) neighbors, not including semi-neighbors. $N(p)$ indicates all the neighbors of the node p.

Definition 2.1. DV(p) is the dominating value of a node p in an ad-hoc network. It is calculated as the following before the construction proceeds:

Initial DV(p) := 0
For each q which q in $N(p)$
  If deg(p) > deg(q)
    then DV(p) := DV(p) + 1
  else if deg(p) < deg(q)
    then DV(p) := DV(p) − 1

When routing groups are constructed initially, the dominating values of mobile nodes are used as parameters in the construction process. Later we will describe how this is done. The dominating value DV(p) is obtained by comparing the bi-directional link connectivity of the node p with that of all its neighbors. Initially DV(p) is zero. It compares with its neighbors by degree values. If the degree of one of its neighbors is less than deg(p), DV(p) is increased by one; otherwise DV(p) is decreased by one in the case that the neighbor's degree is greater than deg(p).

According to the dominating values of mobile nodes, there are three kinds of nodes in an ad-hoc network. A node is a *positive* node, implying that its bi-directional link connectivity is greater than that of most of its neighbors; while, a node is a *negative* node if its bi-directional link connectivity is less than that of most of its neighbors. In addition, a node is a *zero* node, indicating that the bi-directional link connectivity is balanced among its neighbors. In the next section we will discuss how to construct a routing environment by dominating values.

Theorem 2.1. In the initial constructed bi-directional connected network, the summation of all dominating values of nodes is zero.

It is simple to prove the theorem. Let G be a bi-directional connected network. Then the summation of all dominating values in G is zero. If G is a trivial node, it is proved. A node p is added to G to form network G′. There are n bi-directional links between the node p and the network G, where n is greater than zero. Let the node q in G be one of the neighbors of the node p. For each bi-directional link between the node p and the node q, one's dominating value is increased by one and the other one's dominating value is decreased by one. Therefore the summation of all dominating values in G′ is zero, too.

After the construction process, the ad-hoc network will form the routing environment. The terminology of the constructed routing environment will be described in the following definitions.

Definition 2.2. In the constructed ad-hoc network, the link is called a *positive link* if two nodes of a link are both *positive*. Otherwise the link is called *non-positive*.

Definition 2.3. In the constructed ad-hoc network, the path whose intermediate links are all *positive* is called a *positive path*. On the other hand, the path whose intermediate links are all *non-positive* is called *non-positive* path.

As shown in figure 1, nodes D, E, H, I and O are all *positive* and the other nodes are *non-positive*. Obviously links DE, DH, DI, EH, EI and HI are all *positive*. The other links in this ad-hoc network are *non-positive*. The routes, which are from source to destination in a constructed ad-hoc network can be combined by some *non-positive paths* and some *positive* ones. For example, the routing from A

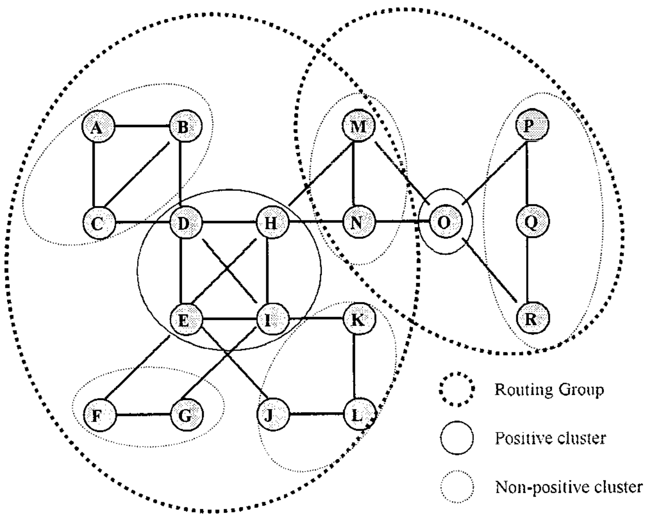

Figure 1. The initial constructed network topology.

to G finds that paths are along *non-positive paths*, *positive paths* and *non-positive paths*.

Definition 2.4. In a constructed ad-hoc network, a cluster formed by all connected positive nodes is called a *positive cluster* (P-cluster). A cluster formed by all connected *non-positive* nodes is called a *non-positive cluster* (N-cluster).

Definition 2.5. A *routing group* (RG) is formed by one P-cluster with its adjacent N-clusters.

Definition 2.6. An *attachable set* is a set of all the *positive* nodes in the same P-cluster with direct bi-directional links to the same adjacent N-cluster.

Definition 2.7. A *bridge cluster* is the N-cluster belonging to more than one RG. On the other hand, the N-cluster belonging to one RG is called a *peripheral cluster*.

In figure 1, there are two routing groups: RG1 and RG2. In routing group RG1, there are one P-cluster and four N-clusters. In routing group RG2 there are one P-cluster and two N-clusters. The attachable set between P-cluster {D,E,H,I} and N-cluster{F,G} is {E,I}. In other words, the bridge cluster between RG1 and RG2 is N-cluster{M,N}. N-clusters{A,B,C}, {F,G}, {J,K,L} and {P,Q,R} are all peripheral clusters.

The attachable set of a peripheral cluster is the access points for the nodes in this cluster. If a node in the peripheral cluster tends to communicate with another one that is not in this peripheral cluster, it must pass through one of the nodes in the attachable set. The bridge cluster is the N-cluster belonging to more than one routing group. In other words, the bridge cluster is covered by more than one routing group. When a node tends to communicate with the node other than the same routing group, it will pass through the bridge cluster. Therefore, the bridge cluster is the "bridge" of two communicating routing groups.

3. Algorithms for the dynamic group routing in ad-hoc networks

The procedures of group construction are developed to model an ad-hoc network in *routing groups*. In such a constructed environment, route discovery is performed by the characteristics of *routing groups*. Later the network topology is changed due to some events of mobile nodes. The routes are thus maintained to apply the current network topology. Finally due to the dynamics of ad-hoc network topology, the routing groups will react to such variations. Therefore, the routing groups are dynamic to be adaptive to such an environment.

3.1. Construction algorithm

When several mobile nodes gather in some area, the network graph is not constructed initially. All the mobile nodes can only communicate with the nodes in their transmitting ranges. A mobile node senses the neighbors and transmitting semi-neighbors. In our approach the ad-hoc network will be constructed like figure 1 by some interactions with neighbors. A mobile node senses the number of its neighbors by broadcasting control beacon signals in a time period. In this phase the plain information is the link connectivity for all the mobile nodes. With the connectivity information on neighborhood, each mobile node exchanges degree message with its neighbors in a time period. After gathering degrees of its neighbors, the mobile node calculates its dominating value and broadcasts the neighbor list with its dominating value to its neighbors. Upon receiving the message of a neighbor list and a dominating value, whether a mobile node propagates the message or not depends on its dominating value and the received dominating value. If the dominating value of the receiver is *positive*, it will propagate the message; if the dominating value of the receiver and the received dominating value are both *non-positive*, it will also propagate the message to its neighbors. The construction algorithm for a mobile node p in the ad-hoc network is derived as the following steps:

(1) Broadcast message deg(p) to all neighbors

(2) Receive message deg(q) from each neighbor q

(3) Calculate DV(p) as definition 2.1

(4) Broadcast message $\{$List(N(p)),DV(p)$\}$ to each neighbor q

(5) Receive message $\{$List(N(r)),DV(r)$\}$ from each neighbor q
For each message $\{$List(N(r)),DV(r)$\}$

Case 1. DV(p) > 0 & DV(q) > 0
Propagate it to all *positive* neighbors excluding q

Case 2. DV(p) > 0 & DV(q) $<= 0$
Propagate it to all *positive* neighbors

Case 3. DV(p) $<= 0$ & DV(q) $<= 0$
Propagate to all neighbors excluding q

Case 4. DV(p) $<= 0$ & DV(q) > 0
Ignore the message

List(N(r)) is the data structure containing the neighbors of mobile node r and transmitting semi-neighbors of mobile node r. Mobile nodes that have received the information will know the topology in the neighborhood of mobile node r. In case 1, message$\{$List(N(r)), DV(r)$\}$ is propagated through the connected *positive* nodes. In case 2, message$\{$List(N(r)), DV(r)$\}$ is received from a *non-positive* neighbor and propagated to the *positive* neighbors. In case 3, message$\{$List(N(r)), DV(r)$\}$ is propagated through the connected *non-positive* nodes. Accomplishing the construction, the connected ad-hoc network forms two types of clusters: P-clusters and N-clusters. Since the neighborhood messages *are* propagated in the algorithm, the node in a P-cluster will be aware of the network topology of its P-cluster and adjacent N-clusters. The node in an N-cluster is only aware of the network topology in its N-cluster and the links between the N-cluster and the attachable sets. The network topology includes both symmetric and asymmetric links. The awareness domain of the *positive* node is called a *routing group*. Because the *positive* node has the topology information of the *routing group*, it can locally derive the paths from one node to the other node in the same routing group.

3.2. Route discovery strategy

After *routing group* construction as in section 3.1, the *positive* nodes maintain the network topology of its *routing group*. The P-cluster in a *routing group* plays the role of topology information center for communication. When a mobile node tends to communicate with other nodes in this ad-hoc network, the routes to the destination node will be found in a hierarchical style. The route discovery strategy is described as the following:

For a route request from the source node s to the destination node d
if *(the node s is non-positive)*
then *it checks the local topology information of its N-cluster*
  if *(the destination node d is found)*
  then *it routes from the node s to the node d directly*
  else *it multicasts intra-group route request message to all the nodes in its attachable sets and waits for reply message*
    if *(all the reply message are failure)*
    then *it issues inter-group route request message to all the nodes in its attachable sets*
    else *it routes by the reply information from one of the nodes in its attachable sets*
else *it checks the local topology information of its routing group*
  if *(the destination node d is found)*
  then *it routes from the node s to the node d directly*
  else *it multicasts inter-group route request message to all the nodes in the attachable sets of all its bridge clusters, which also belong to other routing groups*

The priority of route searching will be easily found in the above-mentioned strategy. At first the route-requesting node finds the routes in its neighborhood. If the routes are not found, it proceeds the intra-group searching in its routing groups. Finally, if they are still not yet found, it issues the request of inter-group route discovery.

For a *non-positive* source node, it must maintain the topology information of its N-cluster. First, it finds the routes from the local topology information. Second, it may consult with the members of its attachable sets to find the routes in its routing groups. If the N-cluster of the source node is a peripheral cluster, only one routing group is included. While the N-cluster of the source node is a bridge cluster, all the overlapped routing groups will be the searching domains. Finally, it will issue inter-group routing request all over the ad-hoc network. The message will be propagated in such a group-by-group style.

For a *positive* source node, it maintains the topology information of its routing group. First, it searches the routes in the local information for intra-group routing. If the destination node belongs to this group, the routes are found; otherwise, it issues inter-group routing request to all the nodes of the attachable sets of all the bridge clusters in this routing group. Like the *non-positive* source nodes, the inter-group routing message will be propagated all over the ad-hoc network.

3.3. Route maintenance

In an ad-hoc network all the nodes are mobile. The dynamic characteristics of nodes will affect routing processes in the network. When a mobile node is switched on, it will join the network by connecting to the nearby mobile nodes. When a mobile node is switched off, the links in its neighborhood will be broken. The routes will be affected while passing through the mobile node. Moreover, because the node in the ad-hoc network is "mobile" it can move from one place to another. The constructed topology will be changed in terms of the dynamic events in the ad-hoc network. In order to retain the routing environment, the system should update the routing environment by passing messages through the network.

In our approach the dynamic events will be modeled as link variations of the mobile nodes. Each link variation is called a micro event. For each micro event there is a micro action to react to such variation. There are two states for a link between two nodes: *connected* or *disconnected*. The dynamic events can be described as a set of micro events. When a mobile node is switched on, it interacts with its nearby mobile nodes. If the *connected* state is detected by each other, the links between the switched-on node and its neighbors are constructed. In other words, there are links changed from *disconnected* state to *connected* state. When a mobile node is switched off, the links between the switched-off node and its neighbors will be destroyed; i.e., the state of these links will be changed into *disconnected* state. When a mobile node is moved from one place to another, it causes several link variations including several disconnected and connected micro events.

3.3.1. Link variation

The link between two nodes may be constructed or destroyed. Such a variation will affect the network topology and our constructed infrastructure. In our model the node may be *positive* or *non-positive*. Combining the link variations and node attributes, the following cases should be taken into consideration to maintain the network topology information. *Hm* and *Hn* are the observed nodes. $\overline{HmHn}$ is the variant link.

Case I. *Hm* is *positive*, *Hn* is *positive* and the state of link $\overline{HmHn}$ is changed from *connected* to *disconnected*.
This case implies that *Hm* and *Hn* are in the same P-cluster. *Hm* and *Hn* will propagate the message "$\overline{HmHn}$ is disconnected" to other *positive* nodes in the same P-cluster. If the P-cluster is still connected, the disconnected link only updates the internal topology of this P-cluster. If the P-cluster is partitioned into two parts by the disconnected link, this routing group is split into two routing groups.

Case II. *Hm* is *positive*, *Hn* is *non-positive* and the state of link $\overline{HmHn}$ is changed from *connected* to *disconnected*. *Hm* is an access point from the N-cluster of *Hn* to the P-cluster of *Hm*. For the node *Hm* it propagates the message "$\overline{HmHn}$ is disconnected" to all the other *positive* nodes in the same P-cluster. *Hn* also propagates this message to all the other *non-positive* nodes in the same N-cluster. In this case the N-cluster may be detached from the P-cluster if the disconnected link is the only link to the P-cluster.

Case III. *Hm* is *non-positive*, *Hn* is *non-positive* and the state of link $\overline{HmHn}$ is changed from *connected* to *disconnected*.
In this case *Hm* and *Hn* propagate the message "$\overline{HmHn}$ is disconnected" to all the nodes in the same N-cluster and its attachable sets. If the N-cluster is still connected, the cluster structure in the routing group is not changed. Otherwise, the N-cluster is split into two N-clusters by the disconnected link.

Case IV. *Hm* is *positive*, *Hn* is *positive* and the state of link $\overline{HmHn}$ is changed from *disconnected* to *connected*. In this case the link between *Hm* and *Hn* is constructed. *Hm* and *Hn* are to propagate the message "$\overline{HmHn}$ is connected" to all the nodes in the same P-cluster. With the constructed topology information *Hm* can decide whether *Hn* is in the same P-cluster or not. If *Hm* and *Hn* are in the same P-cluster, they only update the inner cluster topology. When *Hm* and *Hn* are not in the same P-cluster, which means they are not in the same routing group, *Hm* will propagate the topology information of its routing group to the nodes in the P-cluster of *Hn* by passing the message through link $\overline{HmHn}$. *Hn* will also perform a similar process as *Hm* at the same time.

Table 1
The connectivity dominating variation of *Hm* caused by the link variation of *Hn*.

Initial DV(*Hm*)	Deg(*Hm*)? deg(*Hn*)	Link $\overline{HmHn}$ variation	Updated DV(*Hm*)
P	$>$	*Connected* → *disconnected*	P or N
P	$=$	*Connected* → *disconnected*	P
P	$<$	*Connected* → *disconnected*	P
N	$>$	*Connected* → *disconnected*	N
N	$=$	*Connected* → *disconnected*	N
N	$<$	*Connected* → *disconnected*	N or P
P	$>$	*Disconnected* → *connected*	P
P	$=$	*Disconnected* → *connected*	P
P	$<$	*Disconnected* → *connected*	P or N
N	$>$	*Disconnected* → *connected*	N or P
N	$=$	*Disconnected* → *connected*	N
N	$<$	*Disconnected* → *connected*	N

Note: P: *positive*; N: *non-positive*; →: link state transition from left to right.

Table 2
The connectivity dominating variation of *Hm* caused by the conectivity dominating variation of *Hn*.

Initial DV(*Hm*)	Deg(*Hm*)? deg(*Hn*)	DV(*Hn*) variation	Updated DV(*Hm*)
P	$>$	*Decrement*	P
P	$=$	*Decrement*	P
P	$<$	*Decrement*	P or N
N	$>$	*Decrement*	N
N	$=$	*Decrement*	N or P
N	$<$	*Decrement*	N or P
P	$>$	*Increment*	P or N
P	$=$	*Increment*	P or N
P	$<$	*Increment*	P
N	$>$	*Increment*	N or P
N	$=$	*Increment*	N
N	$<$	*Increment*	N

Note: P: *positive*; N: *non-positive*.

Consequently, the two routing groups are merged into one by such a link construction.

Case V. *Hm* is *positive*, *Hn* is *non-positive* and the state of link $\overline{HmHn}$ is changed from *disconnected* to *connected*. When the *positive* node *Hm* gets connection to *Hn*, it propagates the message "$\overline{HmHn}$ is connected" to all the nodes in the same P-cluster. *Hn* propagates this message to all the nodes in the same N-cluster and its attachable sets. If *Hm* and *Hn* are in the same routing group, *Hn* propagates the topology information of its N-cluster and its attachable sets.

Case VI. *Hm* is *non-positive*, *Hn* is *non-positive* and the state of link $\overline{HmHn}$ is changed from *disconnected* to *connected*.

In this case *Hm* and *Hn* propagates the message "$\overline{HmHn}$ is connected" to the nodes in the same N-cluster and their related attachable sets. If *Hm* and *Hn* are in the same N-cluster, there is only a link added between *Hm* and *Hn*. When *Hm* and *Hn* are not in the same N-cluster but in the same routing group, their two N-clusters will be merged by propagating topology information. When *Hm* and *Hn* are not in the same routing group, *Hm* propagates the topology of its N-cluster and attachable sets to all nodes in the same N-cluster of *Hn* and all the *positive* nodes in the adjacent P-clusters of *Hn*. *Hn* will also perform a similar process as *Hm* at the same time.

3.3.2. Connectivity dominating variation

The link variation of a mobile node will affect the dominating values of its neighbors and itself. The variation of dominating values is likely to affect the routing group structure. Because of the link variation of a neighbor *Hn*, the dominating values of *Hm* may be changed or unchanged. It mainly depends on the following cases in table 1. The first column denotes the node attribute before variation. The second one gives the degree comparison between *Hm* and *Hn*. The comparison of node connectivity degrees is performed either before disconnecting or after connecting. The third column indicates the state of link variation. The fourth column is the node attribute after variation. There are four possible cases that may change the dominating value of *Hm*. On account of the dominating value changing of *Hn*, *Hm* may change its dominating value as the cases in table 2. There are six possible cases in which the dominating value of *Hm* may be changed in terms of the dominating variation of its neighbor *Hn*.

When the dominating value is changed from *positive* to *non-positive*, the variation may disjoin the original P-cluster or join the attached N-clusters. If the link between E and G is disconnected as in figure 2, the dominating value of node

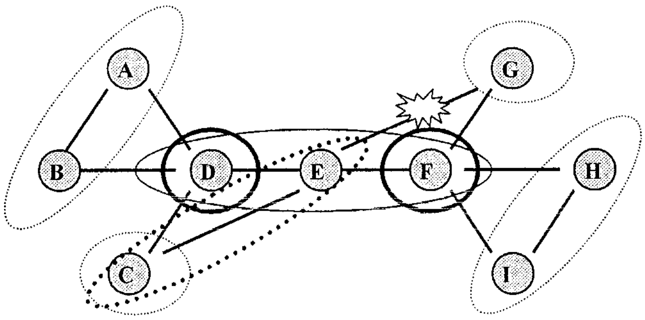

Figure 2. The routing structure changing effect caused by the connectivity dominating variation.

E changes from *positive* to *non-positive*. P-cluster{D,E,F} is split into two P-clusters and node E joins with node C as N-cluster{C,E}. As a result, the routing group will be partitioned into two groups, and N-cluster{C,E} will become the bridge cluster of these two routing groups.

4. Simulation and comparison

The vision of mobile ad-hoc networking is to support efficient operation in mobile wireless networks by incorporating routing functionality into mobile nodes. The system performance depends significantly on its routing schemes. To evaluate our Dynamic Group routing scheme, the simulation results will be shown and compared with some other existing schemes in this section.

4.1. Simulation model

The simulation model consists of several mobile hosts randomly distributed over 1 km $\times$ 1 km area, and each mobile host is with a transmitting range equal to 300 m. The communication range is the circle with radius 300 m from the mobile host. There is a link between two mobile hosts while the distance of two mobile hosts is less than 300 m. A mobile host may be moving or pausing within a time click. It depends on the moving frequency. The maximum moving range is 10 m within a time click. A mobile host may or may not invoke route request within a time click. The moving frequency is the number of moving nodes divided by the number of total nodes in the network. For example the moving frequency is 50% in the 100-node ad-hoc network. We randomly choose 50 moving nodes in a time click. The simultaneous speed of the 50 moving nodes is bound up to 18 km/h. While the moving node moves out of the observed area, we wrap the values of x-axis or y-axis. It also depends on the frequency of route request. We set a time click to be 2 seconds and measure the ad-hoc network execution for half an hour. In the execution time period the program checks moving events and route-request events of mobile hosts. It will evaluate the delay for the topology maintenance and the control traffic over the network in both route maintenance and route discovery phases. Actually the delay is estimated by hop counts of the trip of topology update messages. The control traffic is the number of transmitting control messages for both topology update and route discovery.

4.2. Experimental results

The simulation results are shown as tables 3–5 and figures 3–5. These three data tables are respectively variant in number of mobile hosts, frequency of mobile movements and frequency of route requests in ad-hoc network environment. For each data table there are six rows. The variant factors are listed in the first row. The second row lists three kinds of total numbers: the total number of moving mobile hosts, the total number of route requests and the total number of failure route discoveries. The third row lists the data of total propagation trip (hop count) for DG (Dynamic Group) Routing, Zone Routing and MCDS (Minimum Connected Dominating Set) Routing within the evaluation time period. The fourth row lists the total number of propagating message packets for DG Routing, Zone Routing and MCDS Routing in the maintenance phase. The fifth row lists the total number of propagating message packets for DG Routing, Zone Routing, MCDS Routing and Flood Routing in the route discovery phase. The last row lists the total number of propagating message packets for DG Routing, Zone Routing, MCDS Routing and Flood Routing in both phases.

In addition, three groups of figures are derived from these three data tables. Figures 3(a)–(d) show simulation results for the different mobile host densities; as a result, the more mobile hosts in the same area tend to increase the connectivity in the network. In figures 3(c) and (d), we evaluate the flooding scheme for comparison. Figures 4(a)–(d) show simulation results for the different mobile moving frequencies, implying the changing rate of network topology. Figures 5(a)–(d) show simulation results for the different route request frequencies within the evaluation time period.

4.3. Discussion and comparison

The existing routing schemes applied in the ad-hoc network are classified either as proactive or as reactive [18]. Proactive schemes attempt to continuously evaluate the routes within the network so that the route will be known and can be immediately used when a packet needs to be forwarded. The family of Distance–Vector schemes [2,3] is an example of a proactive scheme. Reactive schemes, on the other hand, invoke a route determination procedure on demand only. The family of classical flooding algorithms is a reactive scheme.

The advantage of proactive schemes is that, once a route is queried, there is little delay until the route is determined. In reactive schemes, route information may not be available at the time a route query packet is received. The delay to determine a route can be quite significant. Moreover, the global search procedure of reactive protocols requires significant control traffic.

Table 3
Simulation results for variant number of mobile hosts with moving frequency is 50% and route-querying frequency is 20%.

Variable	Number of mobile hosts	10	20	30	40	50	60	70	80	90	100
System parameters	Number of movements	4500	9000	13500	18000	22500	27000	31500	36000	40500	45000
	Number of route requests	1800	3600	5400	7200	9000	10800	12600	14400	16200	18000
	Number of failure replies	737	937	153	44	0	0	0	0	0	0
Delay in route maintenance	DG routing(mtc)	806	1990	6322	9297	13187	16281	18468	20828	23496	25785
	Zone routing(mtc)	1153	3149	12579	17721	25913	35491	37864	46756	39832	59783
	MCDS routing(mtc)	4065	8854	8342	12852	16326	20547	26648	31415	35997	36146
Traffic in route maintenance	DG routing(mmc)	1205	4343	15590	28370	40215	50316	60024	69228	78401	87402
	Zone routing(mmc)	2827	12310	69647	153363	296127	558689	766646	1381379	1444654	2427104
	MCDS routing(mmc)	5729	16435	31188	49061	65756	85383	106829	133691	154892	175904
Traffic in route discovery	DG routing(rmc)	2220	14752	16964	23343	28018	31248	36072	40262	44395	49246
	Zone routing(rmc)	4599	67051	136136	302351	446242	706411	1080022	1502704	2097260	2893800
	MCDS routing(rmc)	3859	18180	30917	43615	48645	56594	68738	75647	86509	95643
	Flood routing(rmc)	14213	116963	530394	1255318	2424576	4141092	6519534	9668336	13695498	18709020
Total traffic in route discovery & maintenance	DG routing(tmc)	3425	19095	32554	51713	68233	81564	96096	109490	122796	136648
	Zone routing(tmc)	7426	79361	205783	455714	742369	1265100	1846668	2884083	3541914	5320904
	MCDS routing(tmc)	9588	34615	62105	92676	114401	141977	175567	209338	241401	271547
	Flood routing(tmc)	14213	116963	530394	1255318	2424576	4141092	6519534	9668336	13695498	18709020

Table 4
Simulation results for variant moving frequency of mobile hosts with the number of mobile hosts is 50 and route-querying frequency is 20%.

Variable	Frequency of movement	10	20	30	40	50	60	70	80	90	100
System parameters	Number of movements	4500	9000	13500	18000	22500	27000	31500	36000	40500	45000
	Number of route requests	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000
	Number of failure replies	0	21	68	3	200	0	0	1	0	29
Delay in route maintenance	DG routing(mtc)	8880	10089	11963	11721	11406	12490	12321	11942	12105	14721
	Zone routing(mtc)	18171	24257	25659	19855	24812	25494	24472	26370	23957	28887
	MCDS routing(mtc)	8422	12261	12638	13803	15939	15812	17478	17590	17884	19286
Traffic in route maintenance	DG routing(mmc)	20342	26418	33709	35951	37462	39538	40614	40881	40961	42171
	Zone routing(mmc)	65171	167853	214320	171893	310121	315142	380832	407002	434469	548738
	MCDS routing(mmc)	48953	55517	58112	59694	67077	66213	71013	72359	73105	76115
Traffic in route discovery	DG routing(rmc)	29163	33885	30091	29060	32270	29566	30537	32187	33162	26422
	Zone routing(rmc)	549538	667973	563601	505080	716414	488769	500521	555030	565549	382080
	MCDS routing(rmc)	50629	55571	52585	51544	57901	49273	50724	52536	53978	46790
	Flood routing(rmc)	2425010	2419990	2407251	2421436	2366526	2424946	2425010	2424034	2424322	2414168
Total traffic in route discovery & maintenance	DG routing(tmc)	49505	60303	63800	65011	69732	69104	71151	73068	74123	68593
	Zone routing(tmc)	614709	835826	777921	676973	1026535	803911	881353	962032	1000018	930818
	MCDS routing(tmc)	99582	111088	110697	111238	124978	115486	121737	124895	127083	122905
	Flood routing(tmc)	2425010	2419990	2407251	2421436	2366526	2424946	2425010	2424034	2424322	2414168

Table 5
Simulation results for variant route querying frequency with the number of mobile hosts is 50 and moving frequency of mobile hosts is 50%.

Variable	Frequency of route request	10	20	30	40	50	60	70	80	90	100
System parameters	Number of movements	22500	22500	22500	22500	22500	22500	22500	22500	22500	22500
	Number of route requests	4500	9000	13500	18000	22500	27000	31500	36000	40500	45000
	Number of failure replies	0	0	20	521	0	489	0	0	27	0
Delay in route maintenance	DG routing(mtc)	12112	11383	12514	11160	13210	12176	12660	12518	11501	12157
	Zone routing(mtc)	22702	26066	22378	20776	29314	24283	27581	26827	25154	26340
	MCDS routing(mtc)	15124	13119	17421	15919	17077	15764	15332	14845	15374	14518
Traffic in route maintenance	DG routing(mmc)	39083	38320	39713	37002	39099	38148	39840	39400	39032	39409
	Zone routing(mmc)	285094	295623	265132	232521	349119	264619	344774	328419	298932	285171
	MCDS routing(mmc)	64962	62908	66761	65309	66557	64674	66059	65355	66042	62707
Traffic in route discovery	DG routing(rmc)	14759	32749	41957	57106	72542	89405	99027	120007	141490	155731
	Zone routing(rmc)	148592	528795	893383	2071878	2628902	4262847	4686587	6769821	8608648	10675073
	MCDS routing(rmc)	25151	50265	73228	99253	128294	156793	173273	200391	228637	252165
	Flood routing(rmc)	661219	2425010	5280758	8971639	1.4E+07	2E+07	2.8E+07	3.6E+07	45599107	56224396
Total traffic in route discovery & maintenance	DG routing(tmc)	53842	71069	81670	94108	111641	127553	138867	159407	180522	195140
	Zone routing(tmc)	433686	824418	1158515	2304399	2978021	4527466	5031361	7098240	8907580	10960244
	MCDS routing(tmc)	90113	113173	139989	164562	194851	221467	239332	265746	294679	314872
	Flood routing(tmc)	661219	2425010	5280758	8971639	1.4E+07	2E+07	2.8E+07	3.6E+07	45599107	56224396

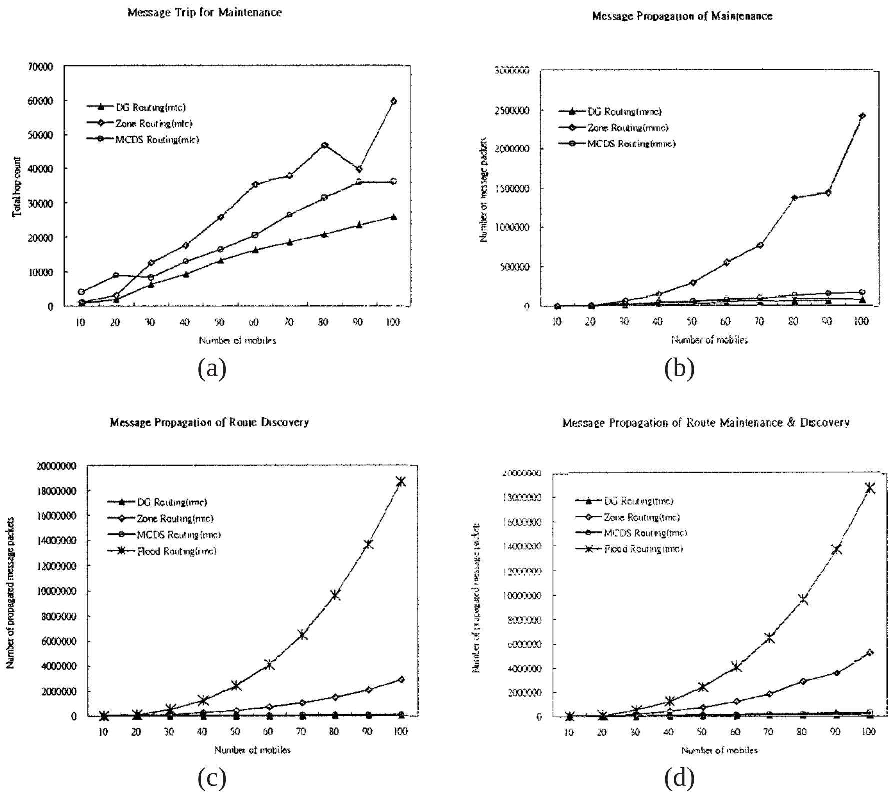

Figure 3. Statistic charts for variant number of mobile hosts. (a) Total delay in route maintenance phase by increasing number of mobile hosts. (b) Control traffic in route maintenance phase by increasing number of mobile hosts. (c) Control traffic in route discovery phase by increasing number of mobile hosts. (d) Total control traffic by increasing number of mobile hosts.

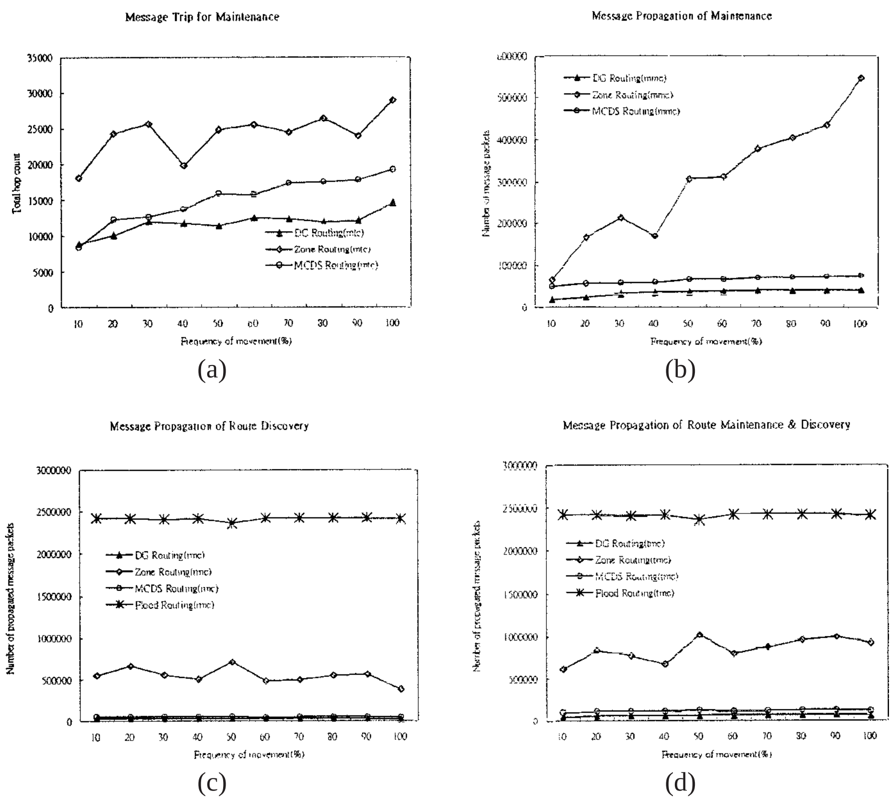

Figure 4. Statistic charts for variant moving frequency of mobile hosts. (a) Total delay in route maintenance phase by increasing moving frequency. (b) Control traffic in route maintenance phase by increasing moving frequency. (c) Control traffic in route discovery phase by increasing moving frequency. (d) Total control traffic by increasing moving frequency.

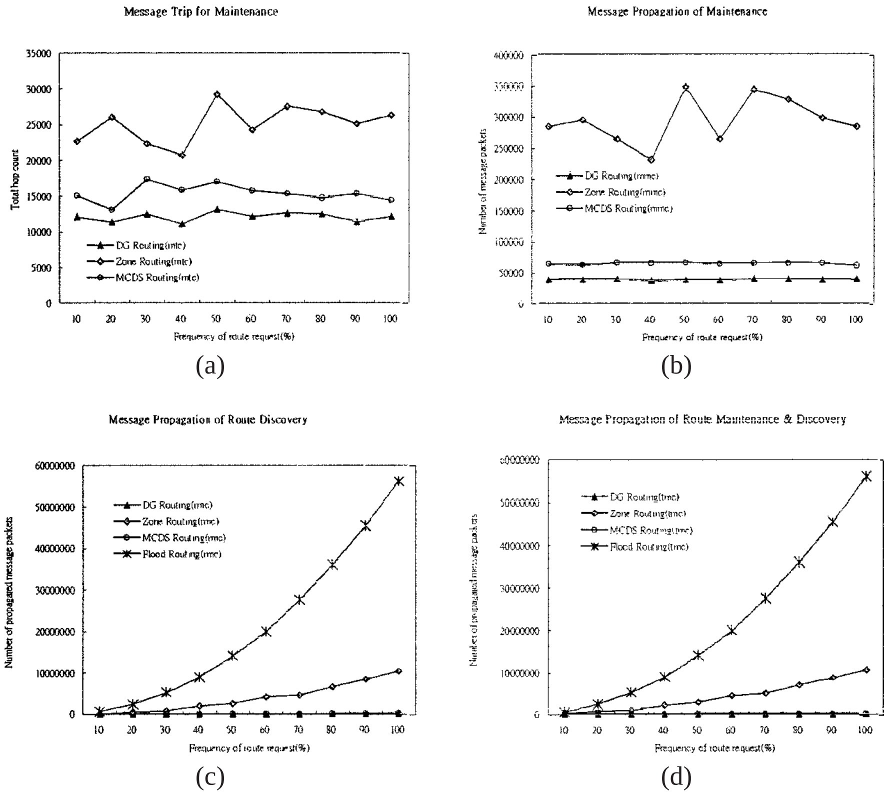

Figure 5. Statistic charts for variant route query frequency of mobile hosts. (a) Total delay in route maintenance phase by increasing routing frequency. (b) Control traffic in route maintenance phase by increasing routing frequency. (c) Control traffic in route discovery phase by increasing routing frequency. (d) Total control traffic by increasing routing frequency.

The massive control traffic in the ad-hoc network will reduce the communication throughput and consume most power dissipation. Because of the long delay and excessive control traffic, pure reactive routing schemes may not be applicable to real-time communication. However, pure proactive schemes are likewise not appropriate for the ad-hoc networking environment, as they continuously use a large portion of network capacity to keep the routing information up-to-date. Since mobile hosts in an ad-hoc network move quite fast and frequently, most of the evaluated routing information is never even used. This results again in an excessive waste of the wireless network capacity.

Most of the routing schemes in an ad-hoc network are a hybrid of reactive and proactive schemes. They initiate the route-determination procedure on-demand, but at limited search cost. These schemes tend to maintain somewhat the network topology. Our approach is one of the hybrid schemes. When a mobile host invokes a route request, at first it performs the route discovery process in its own routing group. The dynamic group is the limited scope of route searching. Therefore, the network topology in this scope should be maintained for the mobile hosts in the P-cluster and the route information of the routing group should be kept in the *positive* nodes in the same routing group. Three hybrid schemes, the Zone Routing approach [18], the MCDS (minimum connected dominating set) Routing approach [1,16] and our Dynamic Group Routing approach, will be chosen and compared in this paper. For the Zone Routing approach, we choose the radius equal to 2.

The Zone Routing scheme is somewhat similar to the uniform cluster-based approach. The local network topology is maintained within the radius. It is a locality dependent scheme. The clusters are formed by the radius coverage. The overlap of clusters is severe while the node density is large. This implies a high frequency of topology updates. Therefore this scheme will pay much overhead in topology updates while the node density is large. The MCDS Routing scheme constructs the minimum connected dominating set as a virtual backbone in advance. It depends on the connectivity of mobile nodes. However, its construction algorithm may apply the global labeling algorithm and some iteration for selecting the maximum connectivity node. The ad-hoc network topology always changes frequently. The response to the changes is a great challenge for this scheme. The network expansion in this scheme will be a little difficult. While a network is expanded, it will be partitioned into many groups. Instead of the partition method being naturally formed, it is performed by expressive determination. In our approach the construction algorithm is more easy and efficient. It only senses the neighbors and their degrees, and then constructs two type of clusters – P-clusters and N-clusters – interleaved all over the ad-hoc network. The routing groups are naturally formed by the scheme. As a result, the route maintenance will become more efficient and less overhead under such a constructed environment.

5. Conclusion

Under the real-time ad-hoc network environment, some characteristics of the ad-hoc network should be considered in designing the routing schemes, such as dynamic topology, power constrained mobile nodes, bandwidth constrained links, etc. In order to improve the system performance, a routing scheme should not be so complicated as to waste the resource of evaluating the volatile routes for the rapid changes in network topology. The rapid response routes are more important for the route requests issuing, in spite of that they may not be the shortest routes. Another important issue in such an environment is that the control message should not massively propagate all over the network. The control message packets must be controlled carefully. In this paper, we propose a two-type clusters scheme to form the routing group structure, maintaining the routing environment in ad-hoc networks. It seems that this approach is adaptive to such a domain for the reaction in the route maintenance phase and the message propagation control in both the route maintenance and the discovery phase. The further works on research about routing in ad-hoc networks are considered to develop protocols to manage the flow control all over the mobile ad-hoc network and some other higher layer issues.

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