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A Stability-Based Clustering Technique and Routing Protocol for Mobile Ad Hoc Networks*

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Clustering is an important technique in mobile ad hoc networks to provide a framework for management and reduce the overhead of route acquisition. Many clustering techniques had been proposed in the literature, but few of them had considered the status of network from the aspect of stability. In this paper, a stability-based clustering (SBC) technique is proposed. SBC only constructs stable enough clusters to reduced maintenance overhead. Therefore, SBC tends to construct more clusters in low-mobility situations and fewer clusters in high-mobility situations. The route finding mechanism combining both unicasting and broadcasting of route request packets is proposed for SBC. Simulation study shows a better performance of SBC than Zone Routing Protocol, Lowest-ID Clustering, and Highest-Connectivity Clustering in terms of maintenance overhead and route finding cost.

Keywords: mobile ad hoc network (MANET), clustering, routing protocol

1. INTRODUCTION

A *mobile ad hoc network* (MANET) [1-3] is a collection of wireless mobile nodes that cooperatively form an autonomous system that operates without the support of any fixed network infrastructure. MANET has been proposed for a variety of goals such as providing a communication platform in hostile or disaster-stricken areas. Networking mechanisms such as routing protocols for MANETs require high efficiency because of limited resources in a mobile node such as network bandwidth, memory capacity, and battery power. However, the nature of dynamic changing topology in MANETs introduces difficulties in end-to-end route finding. Existing routing schemes for MANET can be classified into three categories according to different design philosophies: (1) *proactive*, (2) *on-demand*, and (3) *hybrid* schemes.

A mobile node in a proactive routing scheme maintains routes to other nodes all the time, which means each node in the MANET needs to record and update timely network information to maintain its routing table. Proactive routing schemes provide fast route acquisition at the expense of high maintenance overhead of very dynamic network state. *Fisheye State Routing* (*FSR*) [4], *Optimal Link State Routing* (*OLSR*) [5] are examples of proactive routing scheme.

Mobile nodes using on-demand routing schemes [6-8] do not have to maintain all-time routing tables, but performing a route finding process when a route is needed and

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no available route cached in a mobile node. Comparing with proactive schemes, on-demand routing schemes save the overhead of maintaining the network state all the time at the expense of a longer latency of route acquisition. *Dynamic Source Routing* (*DSR*) [9] and *Ad Hoc On-Demand Distance Vector* (*AODV*) routing [10] are two well-known examples of on-demand routing scheme.

Hybrid schemes try to find a good compromise between proactive and on-demand schemes. The basic idea behind hybrid schemes is to limit the proactive operation within a small domain to reduce maintenance overhead and use on-demand operation for inter-domain routing. The proactive domain is called *cluster* or *zone* in the literature, and the method of forming clusters in a MANET is called clustering technique. Many clustering techniques have been proposed, including *Lowest-ID clustering* [11], *Highest-connectivity clustering* [12], *Weighted clustering* [13-15], *Mobility-based clustering* [16, 17], *Associability-based clustering* [18, 19], *Zone Routing Protocol* (*ZRP*) [20, 21], *etc*. However, only few of them have considered the stability aspect in MANET.

In this paper, we propose a *stability-based clustering* (*SBC*) technique that can dynamically change the state of clustering in MANET according to different stability conditions. More specifically, only stable enough clusters are formed in SBC, which implies that there are mobile nodes not belonging to any cluster in a MANET. As will be shown in simulation results, SBC can adapt to different mobility conditions and obtain a better performance in terms of maintenance and routing overhead.

The rest of the paper is organized as follows. In section 2, we give a brief survey on some of the existing clustering techniques for MANET. In section 3, we present the idea and mechanisms of stability-based clustering. Route acquisition for stability-based clustering is explained in section 4. Simulation results and performance comparisons are presented in section 5. Finally section 6 concludes this paper.

2. RELATED WORK

The objective of the traditional clustering schemes is to find an interconnected set of clusters covering the entire node population in the MANET. Namely, the system topology is divided in to small partitions (clusters) with independent control. A good clustering scheme will tend to preserve its structure when a few nodes are moving and the topology is slowly changing. Otherwise, high processing and communication overheads will be paid to reconstruct clusters. In the following, we give a survey on some of the clustering techniques proposed in the literature.

2.1 Lowest-ID Clustering

Clusters are constructed based on node ID in Lowest-ID clustering [11] with the assumption that each node has a unique ID and knows the ID's of its one-hop neighbors. During cluster construction, the *lowest-ID node* is elected as the cluster head and its neighbor nodes become the cluster members. Properties of the distributed clustering algorithm of Lowest-ID clustering include (1) each node can determine its cluster, (2) any two nodes in a cluster are at most two hops away, and (3) No cluster heads are directly linked. Moreover, the Lowest-ID clustering algorithm partitions the multi-hop MANET into some non-overlapping clusters.

2.2 Highest-Connectivity Clustering

In the Highest-Connectivity clustering algorithm, each node broadcasts the list of nodes that it can hear (including itself). A node is elected as a cluster head if it is the most highly connected node of all its neighbor nodes (in case of a tie, lowest ID prevails). Research showed that the Highest-Connectivity clustering does not perform well from the aspect of stable cluster formation, since when the highest-connectivity node drops even one link due to node movement, it may fail to be re-elected as a cluster head.

2.3 Zone Routing Protocol

Zone Routing Protocol (ZRP) [20, 21] is a hybrid proactive/on-demand routing scheme. Each node maintains a current view of a surrounding region that is referred to as a *routing zone*. The most distant (in hops) nodes of each routing zone are referred to as the routing zone's *peripheral nodes*, and lie at a distance (in hops) called the *routing zone radius*. Note that every node maintains its own routing zone, so that routing zones of neighboring nodes overlap. In order to maintain timely topological information for a routing zone, each node must be notified about the changes of neighbor connectivity within its routing zone.

To find an end-to-end route, a source node sends out a route query packet and waits for the reply from the destination. Knowledge of routing zone topology can be used to direct route queries from a node to its peripheral nodes, rather than just simply flooding queries from a node to all its neighbors. This kind of packet delivery mechanism is called *bordercasting*. By bordercasting queries to peripheral nodes, redundant querying within a routing zone can be avoided.

Overlapping clusters are formed in ZRP since each node maintains its own routing zone. Therefore, the maintenance cost of cluster in ZRP will be much greater than that of the non-overlapping clustering techniques such as Lowest-ID clustering. Moreover, The radius of routing zones affects the performance of ZRP. Simulation studies showed that the overhead of finding an end-to-end route decreases as the routing zone radius increases. However, the amount of intra-zone control traffic required to maintain a routing zone increases with the radius of the routing zone.

3. STABILITY-BASED CLUSTERING (SBC)

3.1 Basic Idea

Most of the existing clustering techniques are aimed at using fewer clusters to cover all mobile nodes in a MANET. Stability of clusters is not the major concern in those techniques. However, an unstable cluster not only poses more maintenance overhead but also doesn't do any good in routing decision and resource management. Thus, from the stability point of view, more clusters should be formed in a stable network condition, fewer clusters in an unstable condition, which is the main idea of the proposed *stability-based clustering* (*SBC*) in this paper. In order to reduce maintenance overhead, only stable clusters are formed in SBC. As shown in Fig. 1, SBC tends to form fewer stable clusters in a high mobility network environment. Fewer clusters in a MANET mean that many of the mobile nodes in the network are not belonging to any clusters and more broadcast packets are used in route discovery. On the other hand, in a low mobility network environment, more stable clusters can be formed, and more unicast packets are used for route finding.

Mobility	High	⟺	Low
Cluster	Fewer	⟺	More
Route	More broadcast	⟺	More unicast

Fig. 1. Stability-based clustering.

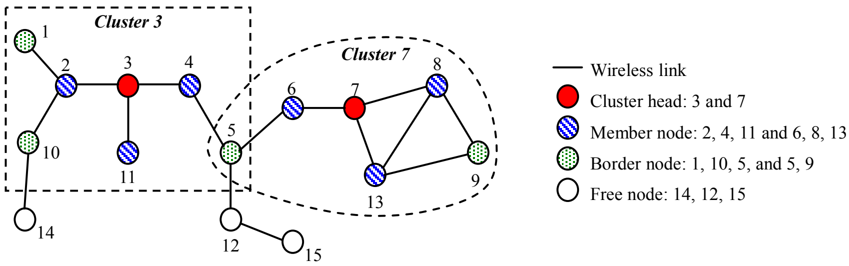


Fig. 2. Example clusters in SBC.

3.2 Clustering Algorithm

A cluster in SBC is defined as a group of connected nodes with 2-hop radius. The center node of a cluster is called *cluster head* and it is responsible for managing the cluster. As illustrated in Fig. 2, a mobile node in SBC can be one of the following roles: (1) *cluster head*, (2) *member node*, (3) *border node*, or (4) *free node*. The cluster head is responsible for maintaining the topological information as well as the membership information in a cluster to support route finding. Member nodes in a cluster are one-hop neighbors of the cluster head. Border nodes are those nodes at the edge of the cluster (*i.e.*, two hops away from the cluster head). Free nodes do not belong to any clusters.

3.2.1 Creating a new cluster

Each node in a MANET starts as a free node and calculates its stability parameter periodically according to the changes of its neighbors. The stability parameter denoted by *StabillityValue* for node v at time period T_n is defined as follows:

$$StabilityValue\,(v, T_n) = \frac{N_1(v, T_n) \cap N_1(v, T_{n-1})}{N_1(v, T_n)},$$

where v is the ID of the node, T_n is the current period, T_{n-1} is the previous period, and $N_1(v, T_n)$ is the number of node v's 1-hop neighbors at period T_n.

It's easy to know that the value of *StabilityValue* is between 0 ~ 1, and a node's *Sta-*

bilityValue is the percentage of its current 1-hop neighbors that were also its 1-hop neighbors at the previous period. Thus, a higher value (*e.g.* close to 1) of *StabilityValue* of a node means that most of the node's 1-hop neighbors remain unchanged for two time periods. Those nodes with a higher *StabilityValue* should be given a higher priority to form a cluster.

We define *StabilityTH* as the threshold value for a node to form a cluster. Only the free nodes with *StabilityValue* larger than *StabilityTH* are allowed to compete and form a cluster. That is, free nodes with *StabilityValue* larger than *StabilityTH* are candidates for cluster head. Moreover, in order to avoid cluster overlapping, we also require that a mobile node be allowed to form a cluster only when all of its 1-hop neighbors are free nodes. The method for candidates to compete and form clusters in SBC is similar to other clustering techniques in the literature. A cluster head candidate broadcasts a message to all its 2-hop neighbors announcing its *StabilityValue*. If none of its 2-hop neighbors has a higher *StabilityValue*, the candidate then announces itself as a cluster head and informs all its 2-hop neighbors that they are now belonging to the newly formed cluster.

3.2.2 Maintaining a cluster

When a new cluster is formed, the member nodes (*i.e.* 1-hop neighbors of the cluster head) have to inform the cluster head of their 1-hop neighbor so that the cluster head can maintain the topological information of the cluster. Since a cluster is a proactive domain as mentioned in section 1, the cluster head is informed of the topological changes (link changes) in the cluster.

3.2.3 Dismissing a cluster

In order to decide if a cluster is stable enough to exist, the cluster head needs to reevaluate the stability of the cluster periodically. Similar to the calculation of *StabilityValue* for a free node, *StabilityValue* for a cluster is the percentage of unchanged cluster members including 1-hop member nodes and 2-hop border nodes:

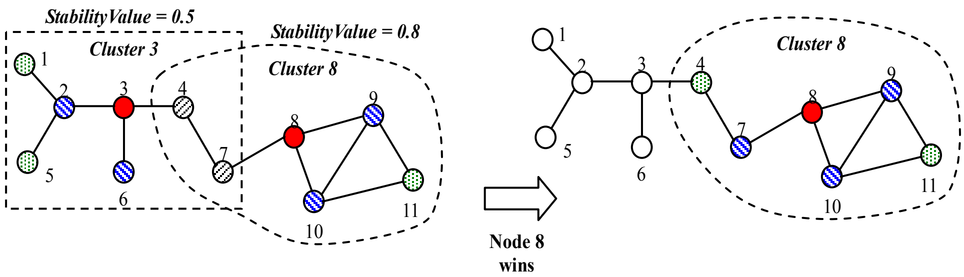
$$StabilityValue\,(v, T_n) = \frac{N_2(v, T_n) \cap N_2(v, T_{n-1})}{N_2(v, T_n)},$$

where v is the ID of the cluster head, T_n is the current period, T_{n-1} is the previous period, and $N_2(v, T_n)$ is the number of members in the cluster.

When *StabilityValue* of a cluster is smaller than *StabilityTH*, the cluster is not stable enough and should be dismissed. In such case, the cluster head sends out a message to all members to dismiss the cluster and makes all members free nodes.

3.2.4 Colliding of two clusters

Normally two cluster heads are at least four hops away in SBC (the case of four hops occurs when two clusters share a common border node). Since nodes in a MANET are mobile, there are cases that two cluster heads come too close such that they are only 3 hops apart. In such case, a mobile node is both a border node of a cluster and a member



(a) Nodes 4 & 7 detects colliding. (b) Node 3 dismisses its cluster.

Fig. 3. *e.g.* Colliding of two clusters.

node of the other cluster. Two clusters that collide (*i.e.* distance between the two cluster heads is smaller than 4 hops) have to compete according to their *StabilityValue* to determine which cluster can survive. The losing one must dismiss the cluster. For example, node 4 (and node 7) in Fig. 3 (a) finds itself to be both member node and border node. Two cluster heads (node 3 and node 8) are informed of the abnormality and start to compare their *StabilityValue*. Fig. 3 (b) shows the results if node 8 wins in the competition.

4. SBC ROUTE FINDING

Similar to the route finding process in typical on-demand routing protocols such as DSR [9], AODV [10], or ZRP [20], a source mobile node in SBC sends out a route finding request. Intermediate nodes in the MANET forward the route request to other nodes until the destination node is reached. When receiving the route request, the destination node sends a reply back to the source node and an end-to-end route is established.

Since there are two different types of route finding domain in SBC: nodes in a cluster (proactive domain) and free nodes (broadcast domain), forwarding of the route request in SBC is a little different from those with homogeneous routing domain. A route request sent by a source node may go through several areas combining proactive domains and broadcast domains until it arrives at the destination node. Forwarding of the route request is unicast-based (using unicast MAC frames) in a proactive domain (cluster), while forwarding is broadcast-based (using broadcast MAC frames) in the broadcast domains (among free nodes).

As a typical example for explaining the route finding process in SBC, we assume a free node wants to find a route to another free node that is two clusters away from the source. Fig. 4 displays a case of the example, where node *S* is the source node and node *D* is the destination node. There are two clusters between *S* and *D*: *cluster* 1 with head node *H*1 and *cluster* 2 with head node *H*2. When *S* wants to find a route to *D*, it sends out a route finding request. Since *S* is a free node, the request is broadcast to all its neighbors. On receiving the request, an intermediate node that is a free node (*e.g.* node *F* in Fig. 4) also broadcasts the request to its neighbors. When node *B* (a border node in *cluster* 1) receives the request that is broadcast by a free node, two things need to be done by node *B*: (1) unicasts the request to its cluster head *H*1, and (2) re-broadcasts the request for free nodes around.

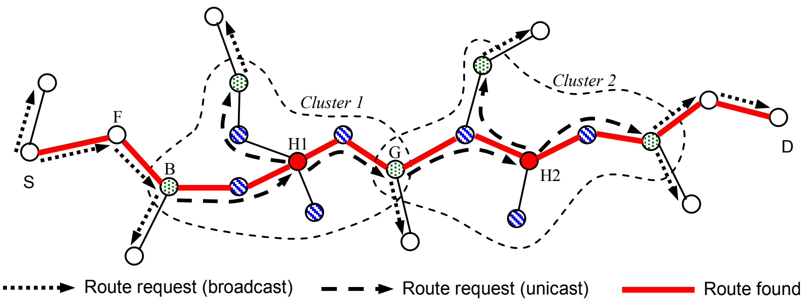


Fig. 4. *e.g.* SBC route finding.

When receiving the request from border node *B* and knowing that the destination node is not in the cluster, cluster head *H*1 unicasts the request to other border nodes in the cluster. Border nodes that receive the request from the cluster head continue to broadcast the request to the free nodes around. Moreover, the border nodes belonging to two or more clusters must act as a gateway for relaying requests between clusters. Hence, in addition to broadcasting the request to free nodes around, node *G* also unicasts the request to cluster head *H*2. The action taken by *H*2 is similar to that of *H*1, and finally the request arrives at node *D*. As in most of on-demand routing protocols for MANET, a route request is only processed once at an intermediate node and each intermediate node relaying a request packet also records the path that the request packet has visited either in the header of the request packet (*e.g.* DSR) or in the cache at each node (*e.g.* AODV). Destination node *D* sends back a reply packet to the source node *S* to establish an end-to-end route and the route finding process is finished.

5. PERFORMANCE EVALUATION

5.1 Simulation Environment and Performance Criteria

Simulation study was conducted to investigate the performance of the proposed SBC scheme. The MANET in the simulation consists of 100 mobile nodes, whose initial positions are chosen from a uniform random distribution over an area of 2000m by 2000m. The *random waypoint* model is adopted as the mobility model for each mobile node, in which a mobile node starts its journey from its initial position to a random destination with a randomly chosen speed (uniformly distributed between 0 ~ 20 m/s). Once the destination is reached, another random destination is targeted after a pause. We vary the pause time, which affects the relative speeds of the mobile nodes. Simulations are run for 5000 simulated seconds. The transmission radius of each mobile node is 250m, which means a communication link exists between two mobiles nodes whose distance are less than 250m.

The criteria for performance evaluation and comparison include: (1) *maintenance overhead* (average number of clustering-related packets per second), (2) *route finding cost* (average number of route request packets generated per route), (3) *average route length* (in hops), and (4) *average lifetime* (in seconds) of the route.

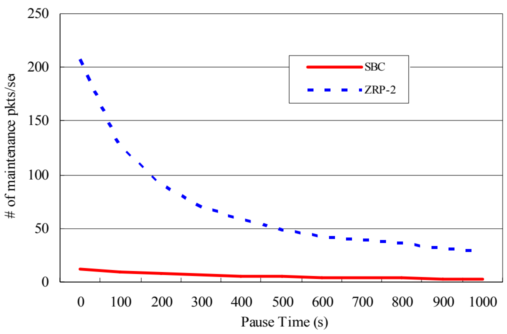
5.2 Performance Comparison

Figs. 5-8 show the results of SBC with 25s refresh period for updating *Stability-Value* (denoted by $T_{refresh}$ = 25s) and *StabilityTH* = 0.5, as well as the results of *Zone Routing Protocol* with 2-hop radius (denoted by ZRP-2).

As shown in Fig. 5, the maintenance overhead of SBC is much smaller than that of ZRP-2 regardless of the value of pause time. The reason is because SBC only forms stable enough clusters (with less changes of link) to reduce maintenance overhead. Moreover, adaptability of SBC to mobility makes the maintenance overhead quite consistent for different values of pause time.

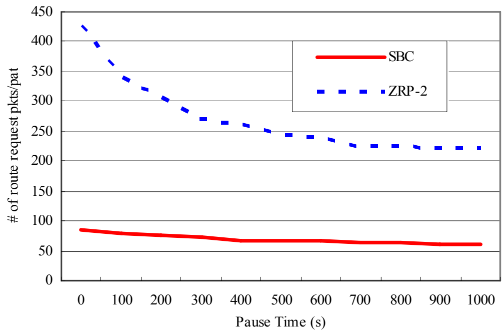
Non-overlapped clustering structure makes the cost of finding a route in SBC much smaller than that of ZRP-2 (with overlapping zones) as displayed in Fig. 6. Broadcast-based forwarding among free nodes in SBC also helps to reduce the number of packets generated in route finding process.

Clustering structure in SBC makes longer routes (1 ~ 2 hops more) than ZRP-2 as shown in Fig. 7 since the route request packet is always forwarded to the cluster head in a cluster, which is apparently not a shortest way to reach the destination. Although the end- to-end route found in SBC is longer than ZRP-2, the average lifetime of the routes in SBC is no shorter (even a little longer in low mobility cases) than ZRP-2 as displayed in Fig. 8.



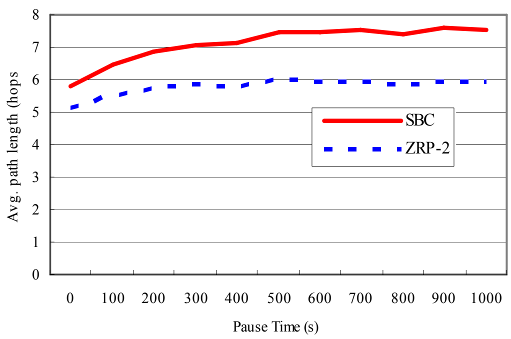
SBC: Refresh period $T_{refresh}$ = 25s, *StabilityTH* = 0.5

Fig. 5. SBC vs. ZRP: maintenance overhead.



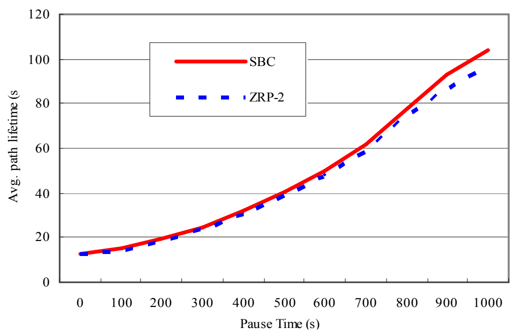
SBC: Refresh period $T_{refresh}$ = 25s, *StabilityTH* = 0.5

Fig. 6. SBC vs. ZRP: route finding cost.



SBC: Refresh period $T_{refresh}$ = 25s, *StabilityTH* = 0.5

Fig. 7. SBC vs. ZRP: average path length.



SBC: Refresh period $T_{refresh}$ = 25s, *StabilityTH* = 0.5

Fig. 8. SBC vs. ZRP: average path lifetime.

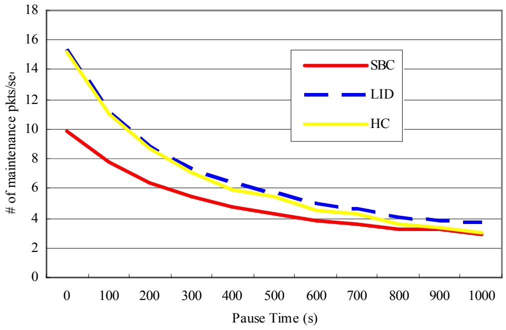


Fig. 9. SBC vs. LID & HC: maintenance overhead.

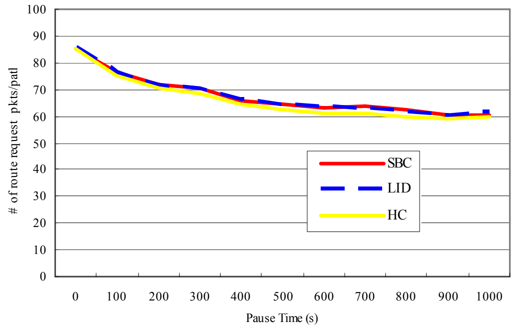


Fig. 10. SBC vs. LID & HC: route finding cost.

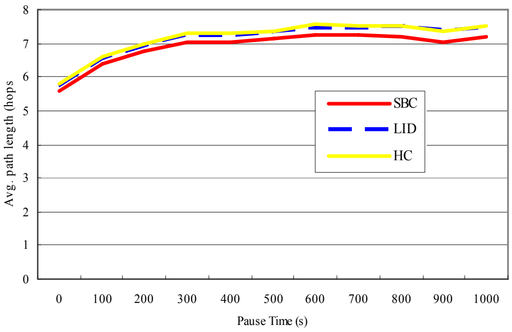


Fig. 11. SBC vs. LID & HC: average path length.

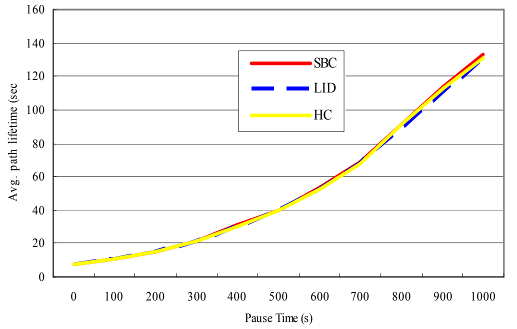
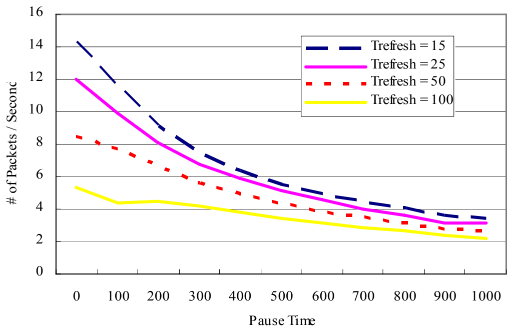


Fig. 12. SBC vs. LID & HC: average path lifetime.

Moreover, Figs. 9-12 show the simulation results for comparing SBC with two non-overlapping clustering schemes that without considering stability aspect: *Lowest-ID clustering* (*LID*) [11] and *Highest-Connectivity clustering* (*HC*) [12]. As shown in Fig. 9, SBC reduces up to 35% of the maintenance overhead (at pause time = 0) over the other two schemes while achieving the same performance level for route finding cost (Fig. 10) and path quality (Figs. 11 and 12: path length and lifetime).

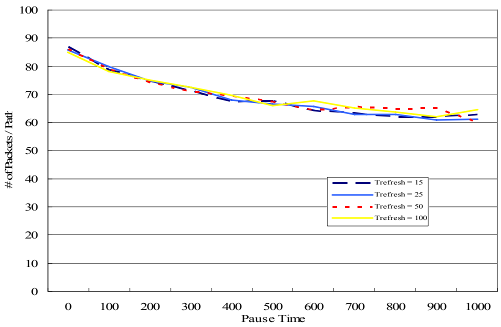
5.3 Impact of $T_{refresh}$ and *StabilityTH*

There are two parameters in SBC that affect the performance: (1) the length of the refresh period ($T_{refresh}$) for updating *StabilityValue*, and (2) the threshold of stability (*StabilityTH*). The longer $T_{refresh}$ is, the fewer clusters are formed and thus the less maintenance overhead as shown in Fig. 13. On the other hand, our experiments show that fewer clusters for a longer $T_{refresh}$ do not affect much the total number of route request packets as illustrated in Fig. 14. That is, the total numbers of route request packets for different values of $T_{refresh}$ are very close. Note that there are two types of route request packets in SBC route finding: broadcast-based and unicast-based. Figs. 15 and 16 display the number of unicast-based packets and broadcast-based packets respectively for $T_{refresh}$ ranging from 15 seconds to 100 seconds. The figures show that a larger $T_{refresh}$ (*e.g.* $T_{refresh}$ = 100 sec) makes fewer unicast-based packets and more broadcast-based packets.



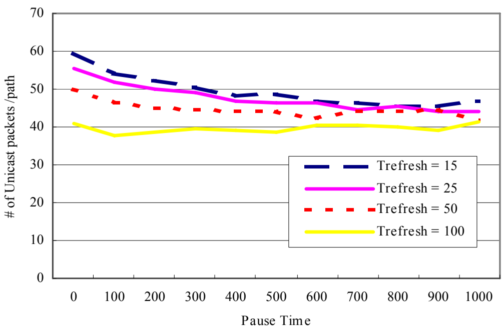
SBC: *StabilityTH* = 0.5

Fig. 13. SBC maintenance cost.



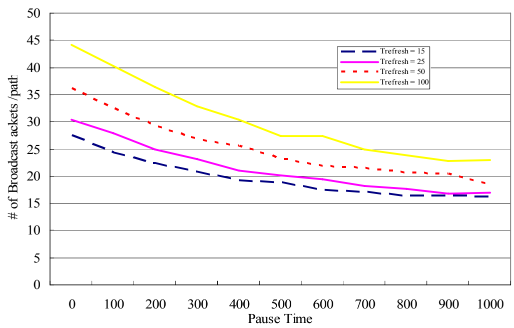
SBC: *StabilityTH* = 0.5

Fig. 14. SBC route finding cost.



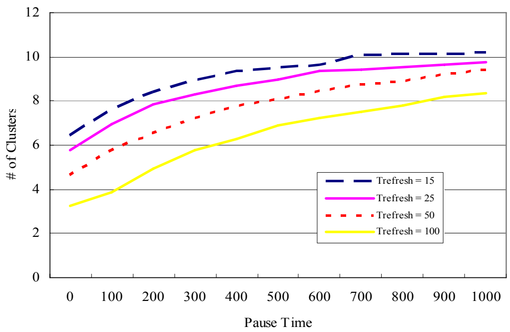
SBC: *StabilityTH* = 0.5

Fig. 15. SBC route finding cost: unicast.



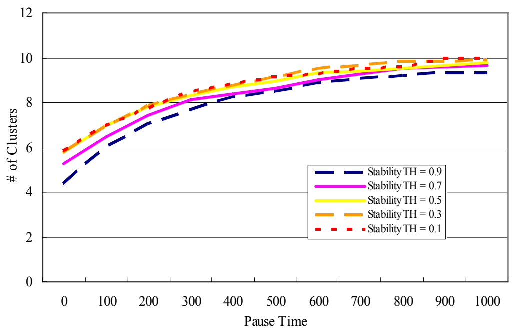
SBC: *StabilityTH* = 0.5

Fig. 16. SBC route finding cost: broadcast.



SBC: *StabilityTH* = 0.5

Fig. 17. Average number of clusters.



SBC: $T_{refresh}$ = 25s

Fig. 18. Average number of clusters.

The average number of clusters formed in the network for different values of $T_{refresh}$ and pause time is displayed in Fig. 17. As we mentioned, fewer clusters are formed for a larger value of $T_{refresh}$. Besides, low mobility (*e.g.* pause time = 1000s) results in more clusters in the network.

The effect of *StabilityTH* is similar to that of $T_{refresh}$, since a lower *StabilityTH* (*e.g.* 0.1) results in more clusters as shown in Fig. 18, and more clusters imply more maintenance overhead. However, the difference of the average number of clusters for different values of *StabilityTH* is not significant. Therefore, the impact of *StabilityTH* on the maintenance overhead and route finding cost is not as much as $T_{refresh}$.

In summary, the selection of $T_{refresh}$ *and StabilityTH* depends on the mobility level of the mobile nodes in the MANET. For the network with high mobility nodes (*e.g.* pause time = 0s), it is better to select a larger $T_{refresh}$ and *StabilityTH* to reduce the maintenance overhead. On the other hand, for the case of low mobility, a smaller $T_{refresh}$ (and *StabilityTH*) can effectively increase the number of clusters such that the amount of broadcast packets in route finding is reduced and the route acquisition time can be shortened.

6. CONCLUSION

In this paper, a stability-based clustering (SBC) technique for mobile ad hoc networks is proposed. Considering that unstable clusters are very easy to collapse due to frequent link changes in the clusters, SBC only constructs stable enough clusters for maintenance and route finding efficiency. Calculation of the stability parameter for a mobile node/cluster is based on the number of unchanged neighbors/members within two consecutive periods of time. Route finding protocol for SBC is also proposed in the paper. Since clusters in SBC are not necessarily covering all mobile nodes in a MANET, the route finding protocol adopts both unicast and broadcast request packets. Simulation results have demonstrated a better performance of SBC than Zone Routing Protocol (ZRP) in terms of maintenance overhead and route finding cost. Although the route found in SBC is in average longer than that of ZRP, simulation results show that the average lifetime of the routes in SBC is no shorter than that of ZRP. Moreover, the simulation results also show that SBC can save up to 35% of maintenance overhead over Lowest-ID clustering and Highest-Connectivity clustering, demonstrating the value of considering stability for clustering in MANET.

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