Available online at www.sciencedirect.com
ScienceDirect
Computer Communications 30 (2007) 453–464
computer communications
www.elsevier.com/locate/comcom

Adaptive backup routing for ad-hoc networks

Wei Kuang Lai [a,*], Sheng-Yu Hsiao [a], Yuh-Chung Lin [a,b]

[a] *Department of Computer Science and Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan, ROC*
[b] *Department of Management Information System, Tajen University, Pingtung 907, Taiwan, ROC*

Received 12 May 2006; received in revised form 19 September 2006; accepted 20 September 2006
Available online 12 October 2006

Abstract

The network topology changes frequently in ad-hoc networks. Some on-demand protocols with multi-paths or backup routes have been proposed to improve the performance in ad-hoc networks. AODV-BR scheme improves AODV routing protocols by constructing a mesh structure and providing multiple alternate routes. The algorithm establishes the mesh and multi-path using the RREP of AODV, which does not transmit many control messages. In this paper, we propose two schemes: AODV-ABR and AODV-ABL to increase the adaptation of routing protocols to topology changes by modifying AODV-BR. In AODV-ABR, the alternative route can be created by overhearing not only RREP packets but also data packets. AODV-ABL combines the benefits of AODV-ABR and Local repair. Finally, we evaluate the performance improvement by simulations.

Keywords: Ad-hoc wireless networks; Routing Algorithm; AODV; Backup route

1. Introduction

In recent years, the progress of communication technology has made wireless device smaller, less expensive and more powerful. Such rapid technology advance has promoted great growth in mobile devices connected to the Internet. There are two variations of wireless networks: infrastructure networks (as shown in Fig. 1) and ad-hoc networks (as shown in Fig. 2). In infrastructure wireless network, there exists a base station (BS) or an access point (AP) to be the portal of wireless devices. Ad-hoc network [3,5,15] is a self-organized, dynamically changing multi-hop network. All mobile nodes in an ad-hoc network are capable of communicating with each other without the aid of any established infrastructure or centralized controller. Each mobile station has a function for routing messages.

The routing protocols supported in infrastructure wireless networks are suitable for one-hop wireless transmission. Many of them cannot be applied directly to the communication in ad-hoc networks because of the characteristics of wireless communication, such as the mobility of wireless nodes. The mobility of wireless nodes will cause the change of network topology. In [25,26], the authors introduced new mechanisms to adapt to the topology variation. The routing algorithm has to react to the topology changes as soon as possible. So, the communication path can remains connected. Many routing protocols have been proposed for ad-hoc networks [2,4,16,17,19,21]. These routing protocols can be divided roughly into two types, table-driven and on-demand routing protocol [19]. Table-driven routing protocols, such as Destination-Sequenced Distance-Vector routing (DSDV) [17], attempt to keep a global picture of network topology and respond to topological changes by propagating update messages throughout the wireless network. One or more tables are required to maintain consistent, up-to-date routing information for each node in the wireless network. In a highly mobility network environment, to maintain the routing information fresh causes heavy overheads.

* Corresponding author. Tel.: +886 7 5252000 4312.
E-mail addresses: wklai@cse.nsysu.edu.tw (W.K. Lai), yuhchung@mail.tajen.edu.tw (Y.-C. Lin).

0140-3664/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2006.09.011

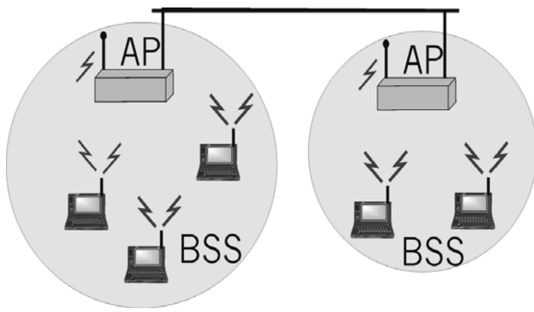


Fig. 1. Infrastructure network.

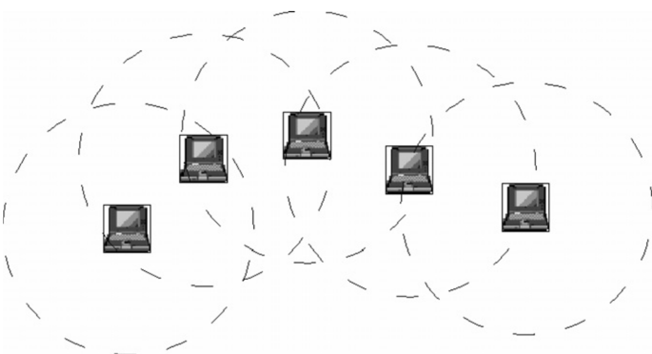


Fig. 2. An ad-hoc network.

Recently, the on-demand routing protocols for ad-hoc network are appealing because of their low routing overheads and effectiveness when the frequency of route re-establishment and the demand of route queries are not high. The route is created only when it is desired by the source node in the on-demand routing protocols. Many on-demand routing protocols have been proposed in [4,14,16,21]. High routing overheads usually have significant impacts on performance in low-bandwidth wireless links. Therefore, the reactive on-demand routing algorithms where routing paths are established only when required are the recent trend in ad-hoc networks, such as the Ad-hoc On-Demand Distance-Vector (AODV) routing protocol.

In the AODV protocol, there is only a single path established during the transmission. Therefore, when the transmission path fails, data packets are simply dropped by nodes along the broken path. For a time sensitive traffic, it's not acceptable to drop too many packets in the period of path failure. For TCP connections, due to packets dropping, it may reduce the performance considerably. Many on-demand protocols with multi-paths or backup routes have been proposed in order to alleviate these problems [1,6–13,21–26]. Multi-path and backup routes could be formed by many different ways. New route discovery is needed only when all paths fail. This could reduce both route discovery latency and routing overheads. Multiple paths can also be used to balance loads by forwarding data packets on multiple paths at the same time [7]. In this paper, we propose two schemes: AODV-ABR (Adaptive Backup Route) which takes advantage of overhearing of RREP and data packets and AODV-ABL (Adaptive Backup Route and Local repair) which integrates the local repair scheme into AODV-ABR. Both schemes can increase the adaptation of routing protocols to topology changes.

The rest of this paper is organized as following. In Section 2, we review some related works. In Section 3, our schemes are proposed. Section 4 presents the simulation results. Finally, Section 5 summarizes key results and issues.

2. Related works

The Ad-hoc On-demand Distance-Vector (AODV) routing algorithm [14,16] is a routing protocol designed for ad-hoc mobile networks. AODV is capable of both unicast and multicast routing. It maintains these routes as long as they are needed by the source node. Operations of unicast routing on AODV can be simply divided into three parts: route request, route reply and route maintenance [14,16].

When the node mobility speed rises or the transmission path is long, the probability of link failures in active routes also rises. The source node may encounter another link failure before current failure fixed. Therefore, to improve the transmission performance, a local repair mechanism [1] has been added to AODV which tries to repair the link error without informing the source node and interrupting the data delivery. The upstream node of the broken link will initiate the local repair process. It broadcasts a RREQ for the destination. The process may cause the flooding of RREQ messages to the entire network. To limit the hop count of the repaired path, the TTL field of the RREQ message which is broadcasted by the upstream node of the broken link will be set to a limited number which is the last known distance to the destination plus a small value [1]. On the other hand, to prevent the forming a loop, the new sequence number, incremented by one, for the destination is also assigned to the RREQ. If the RREQ is delivered to the destination successfully, a substitute path is established. If the first attempt of route repair is unsuccessful, the upstream node of the broken link will send a RERR to the source node. After receiving the RERR, the source node will initiate a new route discovery process.

Based on AODV routing protocol, Sung-Ju Lee and Mario Gerla proposed a new scheme called AODV-BR (Backup Route) [8] which can improve the performance of the AODV routing protocols by constructing a mesh structure and providing multiple alternate routes. When establishing the mesh and looking for multi-path routes, the algorithm takes advantage of the RREPs (Route Replies) messages of AODV without generating additional control messages. In AODV-BR [8], the alternate routes are constructed by the RREP packet. Each neighboring node overhears the RREP packets and records the source of one of RREP packets as the next hop to the destination into its alternate route table. Fig. 3 shows the construction procedure of alternate route table. The established mesh structure of the primary route and the alternate routes looks like a fish bone as shown in Fig. 4.

In AODV-BR [8], the establishment of alternate routes rely on the overhearing of Route Reply (RREP) messages. No additional messages are required during the establishment of alternate routes. With the help of these backup routes, AODV-BR can offer more stable connections than AODV can. However, AODV-BR has to pay extra efforts in the maintenance of alternate route tables and in route recovery. This cost needs to be taken into account when we consider the benefits it can gain. AODV–LR tries to repair the link error without informing the source node and without the disruption in the data delivery. The transmission performance can be improved because of that no data retransmissions from the source are required if link failures can be repaired locally. However, the local link repairs might increase the hop counts of the data path and then enlarge the end-to-end delays. To this problem, a threshold can be used to decide which policy should be taken – to start a local repair process or to conduct a new route discovery process. Our approach possesses positive attributes from both AODV-BR and AODV–LR. The alternate routes are established by the help of overhearing the RREP messages and the data packets. In addition to possible topology variations, local repair scheme with a

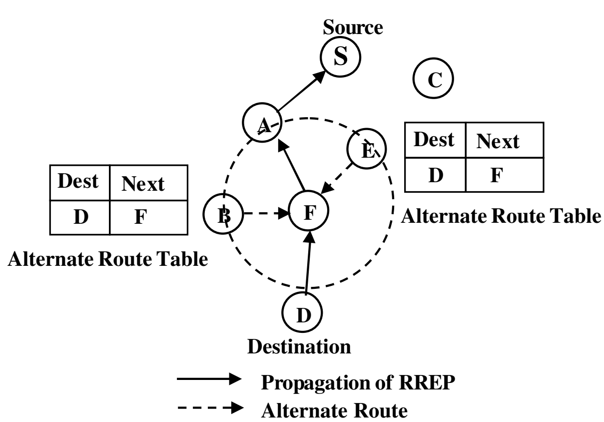


Fig. 3. The procedure of alternate route construction in AODV-BR.

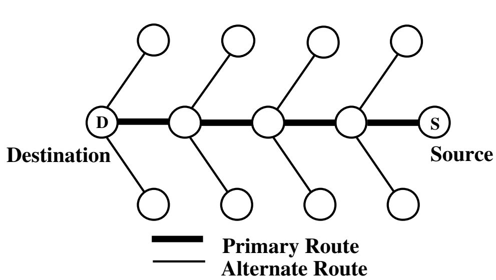


Fig. 4. A fish bone structure formed by the primary route and alternate routes.

triggering threshold is also added into our schemes to improve the transmission performance. The detailed operations will be explained in Section 3.

3. AODV-adaptive backup routing (ABR) and AODV-adaptive backup with local repair routing (ABL)

In AODV-BR, it is appropriate to construct the alternate paths during the route reply phase. It makes the management and maintenance of alternate paths easier. However, when the topology changes more dramatically (i.e., the speed of movement increases), those alternate paths which were constructed during the reply phase may also be broken when the primary route fails. Because the network topology changes frequently in ad-hoc networks, it certainly will need a routing protocol which is more adaptive to the topology variations.

In our proposed mechanism, the operations are similar to the original AODV. Therefore, each routing table and alternate route table also contain following information [1,14,16]:

- Destination
- Next hop
- Hop count
- Destination sequence number
- Expiration time

Next, we will describe the operations of AODV-ABR which are different from the original AODV. The detailed algorithms are listed in appendix.

3.1. AODV with adaptive backup routing (AODV-ABR) protocol

In AODV-BR, a route is time out when the node cannot overhear data packets transmitted by the next node to the destination as indicated in the alternate route table. We extended this technique to construct the mesh structure. In addition to constructing alternate routes by overhearing RREP packet, the mesh structure also can be created by overhearing the data packets transmitted from neighbor nodes. In this way, we can increase the adaptation of routing protocol to topology changes without transmitting many extra control messages. In original AODV protocol, the RREQ and RREP messages contain the information of hop count. Our proposed mechanism also keeps the information of hop count in the routing table and alternate route table, as shown in Fig. 5. Also, the hop count information must be added into the header of data packet. When a node is looking for the routing table, the hop count information has to be updated before forwarding the data packet.

Fig. 5(a) shows the establishment of the primary and alternate routes when the RREP reaches the source node *S*. Fig. 5(b) illustrates the extended usage of “data overhearing” to construct another alternate routes. After a

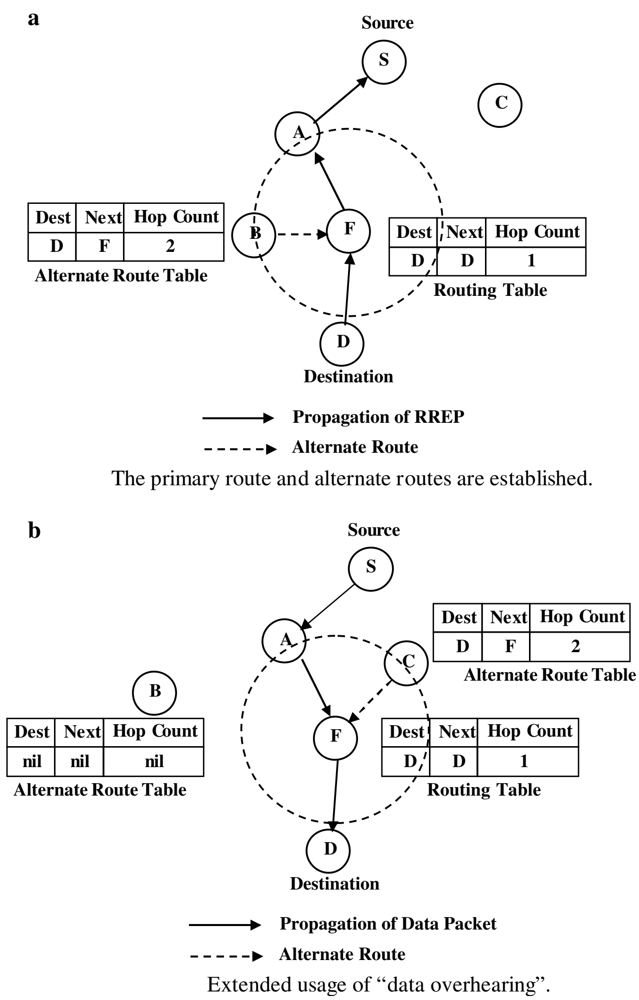


Fig. 5. Update of alternate routes in AODV-ABR.

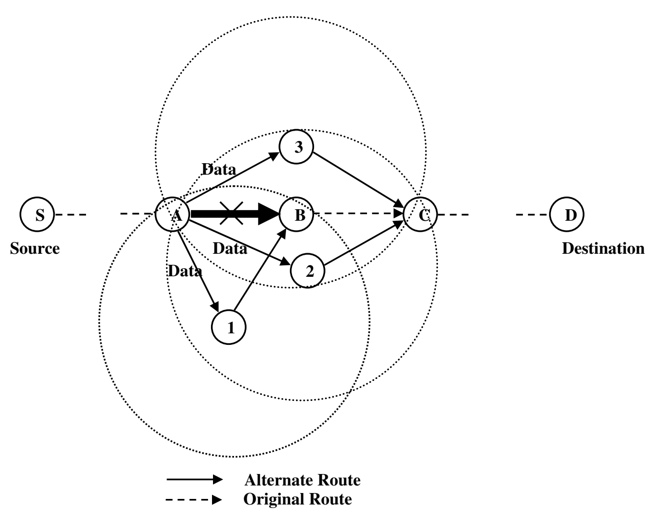


Fig. 6. Extra packet transmissions in AODV-BR.

period of time, node *B* is out of the radio range of node *F* and node *C* moves into the radio range of node *F*. When node *B* does not overhear data packets that were transmitted by node *F* to the destination for a timeout interval, those routing information in alternate route table of node *B* will be removed. And node *C* will record node *F* as the next hop to the destination in its alternate route table after overhearing data packets that were transmitted by node *F* to the destination. Algorithm 1 in Appendix shows the peeking procedure for AODV-ABR.

3.2. Broken link repair

When a node detects a link failure in AODV-BR, it will perform a one-hop data broadcast to its neighbors which forwards those packets to destination via alternate route, and then also send a RERR packet to the source node to reinitiate a route discovery. The "one-hop data broadcast" will result in poor effectiveness under heavy traffic networks because it will create some unnecessary and duplicated data packets delivered through the alternate routes. Fig. 6 is an example showing this problem. When the link between node *A* and node *B* failed, node *A* broadcasts the data packets to its neighbors via alternate paths. Then nodes *1*, *2* and *3* will relay those data packets to the destination node. Those redundancy packets will result in heavy load especially in heavy traffic condition.

On the contrary, when a node detects a link break in AODV-ABR, it will perform a handshake process with its immediate neighbors to repair the broken route instead of a one-hop data broadcast to its immediate neighbors. The handshake process is accomplished by two one-hop control signals: BRRQ (Backup Route Request) and BRRP (Backup Route Reply). The format of BRRQ and BRRP messages are shown in Fig. 7. BRRQ is a broadcast message which contains the destination IP of the transmission path, the originator IP and an ID for this message. BRRP is a unicast message which contains the BRRQ's ID, the IP of the node which responds to the BRRQ, the IP of the node which initiates the broken-link-repair process and a hop count field that indicates the distance to the destination. Therefore, according to the hop count, the upstream node of the broken link (originator) can select a shorter alternate route. Fig. 8 is an example showing how this process is accomplished. When the link break occurs between node *B* and node *C* (see Fig. 8(a)), node *B* will broadcast a one-hop BRRQ signal to its immediate neighbors. Then node *E* and node *F* will reply a one-hop BRRP signal with the hop count to the destination to node *B*. Those replied signals notify node *B* that it can transmit

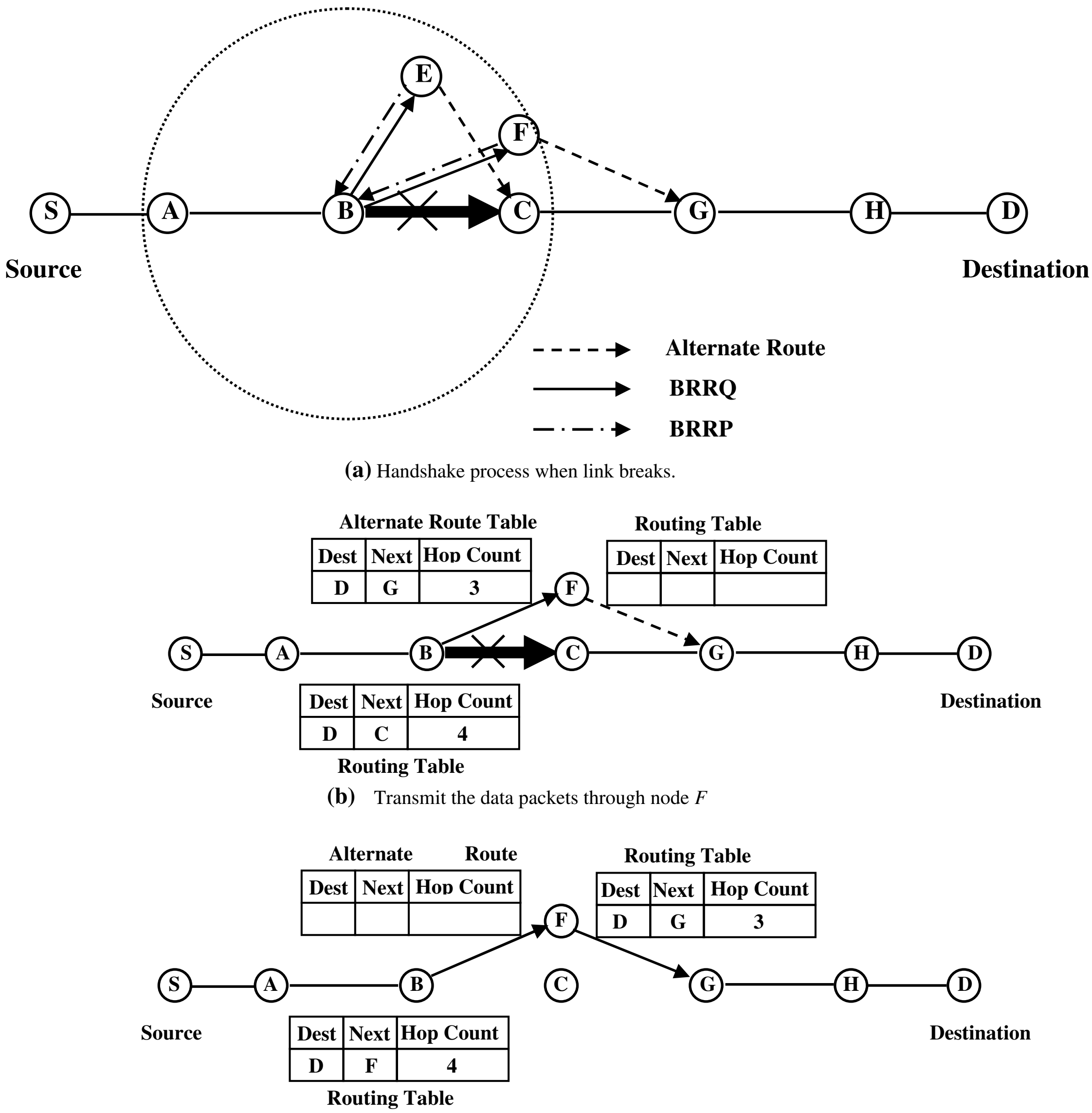
ID	Destination IP	Originator IP

(a) Backup Route Request (BRRQ) message

ID	Originator IP	Transmitter IP	Hop Count

(b) Backup Route Reply (BRRP) message

Fig. 7. The format of BRRQ and BRRP messages.



(a) Handshake process when link breaks.

(b) Transmit the data packets through node *F*

(c) The link break is repaired by updating the next-hop field of routing table in node *B* and copying the information of the alternate route table into the routing table in node *F*.

Fig. 8. Re-route of data packets in AODV-ABR.

the data packets to the destination through node *E* or node *F* by alternate routes. In Fig. 8(b), node *B* will choose node *F* as the next hop to destination according to the hop count, and then transmit data packet to node *F*. Node *B* will update its routing table to reflect this change and node *F* will also copy the routing information from the alternate route table to the routing table (see Fig. 8(c)). Then the broken link is repaired. However, in Fig. 8(a), if node *B* does not receive any reply signal after a waiting period, it will transmit a RERR signal back to the source node. The source node will reinitiate a new route discovery process. Algorithm 2 shows the handling procedure when a link break occurs. Algorithm 3 shows the handling procedure when a BRRQ is received.

A transmission loop has to be prevented when trying to establish an alternate route. The upstream node of the broken link will broadcast a BRRQ message and wait for a BRRP message. The BRRQ packet will be responded by the node which has an alternate route in its alternate route table only when the BRRQ packet is not transmitted by the next hop node to the destination. When the upstream node of the broken link receives a BRRP message, the broken link will be repaired as described above.

In AODV-ABR, an aging technique is also used for alternate route maintenance. If the node that provides the alternate route can overhear data packets transmitted by the next hop node to the destination, it will renew the path information. If the renewal period of the alternate path overruns a timeout interval, it means that the alternate path is no longer required or the node is out of the transmission range of its next hop to the destination. The node removes the alternate path entry from the alternate route table.

3.3. AODV-ABL: combination of ABR and Local repair

When analyzing the difference between AODV–LR (Local Repair) and AODV-ABR, we find that AODV–LR will repair the link locally if the broken link is not far away from the destination, but AODV-ABR could repair the link anywhere along the primary route if alternate routes exist. However, the searching range of repair in AODV–LR is wider than AODV-ABR, which means AODV–LR has a higher probability to find an alternate route to the destination than AODV-ABR. Therefore, we combine AODV-ABR with the Local repair algorithm, and propose a scheme called AODV-ABL (ABR and Local repair). When the distance between the broken link and the destination is not farther than MAX_REPAIR_TTL hops [1], AODV-ABL would try to repair the link by broadcasting a RREQ control signal, just as AODV-LR, and if the broken link is far away from the destination (i.e., the distance is larger than MAX_REPAIR_TTL hops), AODV-ABL will repair the link by a handshake process with immediate neighbors. Algorithm 4 shows the handling procedure when a link breaks in AODV-ABL.

4. Simulation and analysis

4.1. Simulation environment

In this section we simulate an ad-hoc network by modifying GloMoSim network simulator [18,20] to investigate the performance of our proposed schemes. Totally, 30 different scenarios are simulated and the results are averaged. The simulation environment is a 1500×300 square meters, where 50 nodes are randomly distributed. Node pairs are randomly selected to generate CBR/UDP traffic. Channel bandwidth is 2 Mbps. The path loss model is Two-Ray Ground Model. The CBR data packet size is 512 bytes and the packet rate is 4 packets per second. The detailed simulation parameters are listed in Table 1. The random waypoint mobility model is used in our simulation. Each node randomly selects a position, and moves toward that location with a randomly generated speed between the minimum and the maximum speed, which is 0 and 20 m/s, respectively. Once it reaches that position, it becomes stationary for a predefined pause time. After that pause time, it selects another position and repeats the process as mentioned above. We change the pause time to simulate different mobility rates. The pause time is set from 0 to 300 s. When the pause time is equal to 300 s, it means all nodes stay still during the simulation. We would also like to present the performance when there is no movement for every node. According to the suggestion in [1,14], the value of MAX_REPAIR_TTL is set as following equation: MAX_REPAIR_TTL $= 0.3 * $ NET_DIAMETER, where NET_DIAMETER is the maximum possible number of hops between two nodes in the network. In a real-life scenario, the NET_DIAMETER can be estimated according to the hop count from the source to the destination which can be discovered during the route discovery process. In our simulation NET_DIAMETER is approximate equal to eighteen. Therefore, for simplicity, we predefined MAX_REPAIR_TTL as 5 hops.

Table 1
Simulation parameters

Parameter type	Parameter value
Simulation time	300 s
Simulation terrain	1500×300 m
Number of nodes	50
Mobility model	Random waypoint
Mobility	$0 \sim 20$ m/s
Temperature	290 K
Path loss model	Two-ray
Radio frequency	2.4 GHz
Channel bandwidth	2 Mbps
MAC protocol	802.11
Transmission range	250 m
CBR data sessions	10
CBR data rate	4 packets per second
Packet size	512 bytes

4.2. Packet delivery ratio

In this section, we present the throughput in packet delivery ratio. Packet delivery ratio is defined as the total amount of data received divided by the total amount of data transmitted during the simulation. We will compare the five schemes: AODV, AODV-BR (Backup Route), AODV-ABR (Adaptive Backup Route), AODV–LR (Local repair), and AODV-ABL (combination of ABR and LR) in different pause time. Simulation results are shown in Fig. 9. Longer pause time implies less mobility. Therefore, we can see that packet delivery ratio is higher as the pause time increases.

Because AODV simply drops data packets when a route becomes disconnected, the packet delivery ratio of AODV is the worst one among the five schemes. AODV-BR only overhears the RREP message and simply uses the alternate routes to redirect the data packets to go around the broken link. Then it initiates a new route discovery process. The duplicate transmissions through different alternate routes may cause serious collisions and reduce the packet delivery ratio. AODV-ABR constructs the mesh structure by overhearing both the RREP message and data packets. It is more adaptive to the variation of network topology. Therefore, the performance of AODV-ABR is better than AODV-BR. In Fig. 9, we notice that AODV-ABR has better performance than AODV–LR when pause time is longer than 100 s. In a short pause time environment, which means the network topology varies frequently, AODV–LR performs a local repair when the distance to the destination is not farther than MAX_REPAIR_TTL, or initiates a new route discovery. Therefore, the established

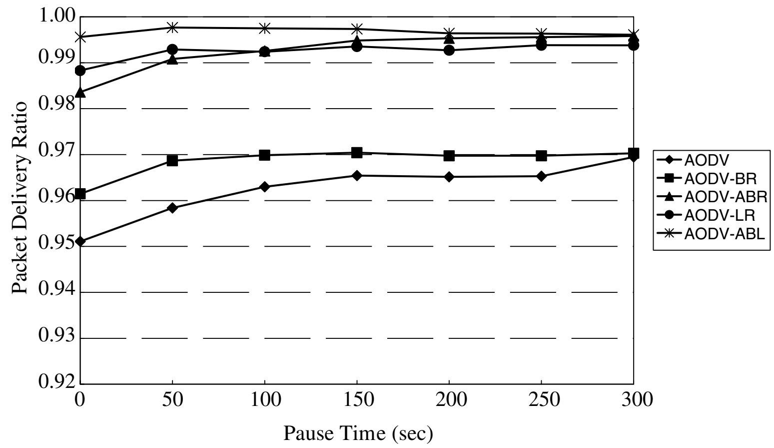


Fig. 9. Packet delivery ratio.

route in AODV–LR is better than the route built in AODV-ABR in a frequently varying environment. When the pause time is longer than 100 s, AODV-ABR performs better than AODV–LR. AODV-ABL attempts to transmit packets with either adaptive backup routing or local repair in the presence of a route break. It takes the advantages of both AODV-ABR and AODV–LR. Hence, AODV-ABL is able to delivery more packets to the destination than another four schemes.

4.3. End-to-end delay

The result of end-to-end delay is presented in Fig. 10. We only measure delays for data packets that reach their destination successfully without considering the cost of route rediscovery process. If we take into account the cost of route rediscovery, the number of re-initiation of new route discovery will tremendously affect the transmission performance. Our proposed schemes effectively reduce the overhead of reinitiating route discovery process. However, we ignore the effect of the route rediscovery process and focus on the end-to-end delay. Because AODV and AODV-BR will re-construct the primary route in the presence of route breaks, the routes for packet deliveries are almost the optimal paths from the source to the destination during the transmission. Therefore, the End-To-End Delay is shorter than other schemes. However, in order to deliver more packets to the destination, AODV-ABL, AODV–LR and AODV-ABR try to repair the broken route locally. The transmission path may go through a long distance from the source to the destination when several link failures occur. Some modifications can be made, such as set a threshold for the number of route repairs. When the number is over the threshold, a new route discovery process will be initiated to establish a near optimal route for the current network topology. This may improve the delay performance of AODV-ABL, AODV–LR and AODV-ABR.

4.4. Hop counts

Fig. 11 illustrates the average hop counts between the source and the destination. The result shows that AODV-ABL and AODV–LR have longer average hop counts

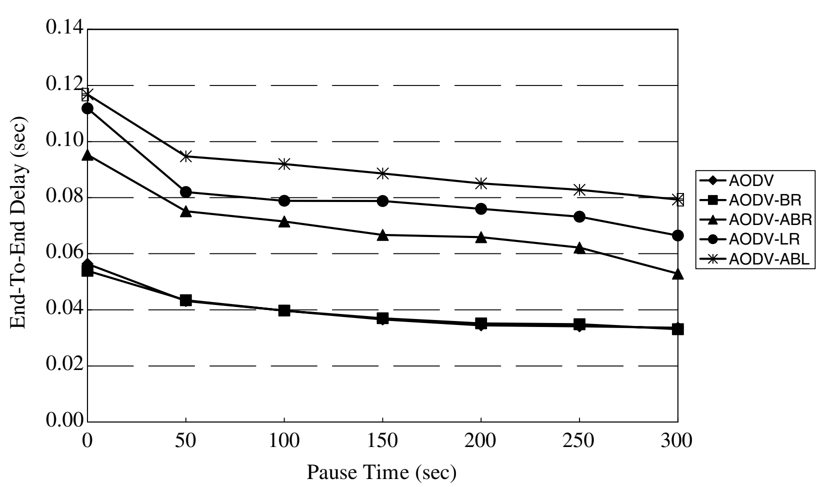


Fig. 10. End-to-end delay.

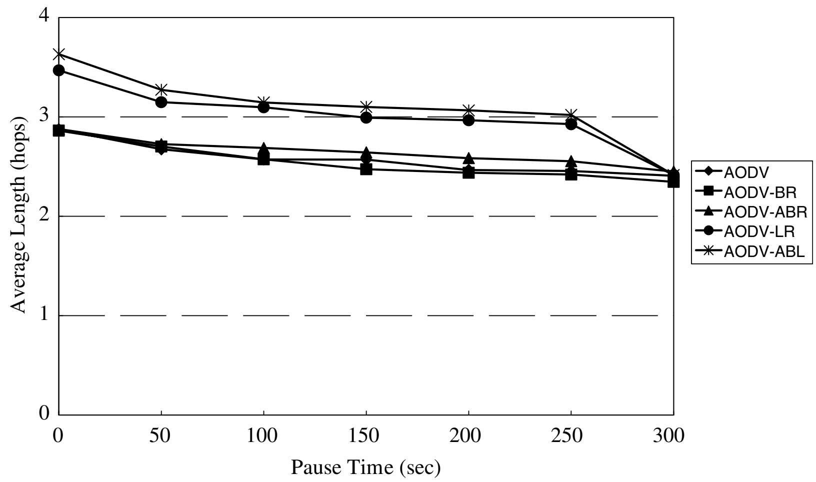


Fig. 11. Hop count.

because they try to repair the broken routes. AODV and AODV-BR do not repair the broken route and use the newer primary route to delivery data packets, so they may have shorter hop counts. When the pause time is equal to 300 s, there is no movement for each node. The topology does not change during the simulation. Therefore, the hop counts for different mechanisms are very close.

4.5. Control overheads

The control overheads are defined as the average number of control messages for one successful packet transmission. As we can see in Fig. 12, the control overhead is lower as the pause time increases. Due to less variations of network topology when the pause time increases, the link failures caused by node mobility are also less, i.e. the primary route is stable. Therefore, no matter what scheme is used, the control overheads are decreased. In Fig. 12, the control overheads of AODV–LR and AODV-ABL are higher than the other schemes because of the broadcast nature of the local repair scheme. On the other hand, AODV-ABR repairs the link failure by only inquiring immediate neighbor nodes. Therefore, it has smaller control overheads than AODV–LR which uses flooding technique to repair the fail routes. Because the conventional AODV and AODV-BR do not repair the route when a link failure occurs, they both have smaller control overheads compared to the other schemes, but also have poor performance in packet delivery ratio.

4.6. The impact of traffic load

We would like to examine the impact of increasing traffic load on these routing protocols. We simulate two scenarios. In the first scenario, the number of sessions remains unchanged during the simulation which is 10. The transmission rate for each session is varied in each simulation. In the other scenario, we increased the number of transmission sessions where each session is with the same transmission rate, 4 packets per second. Figs. 13 and 14 show the packet delivery ratio with transmission rate of 6 and 8 packets per second, respectively. When comparing

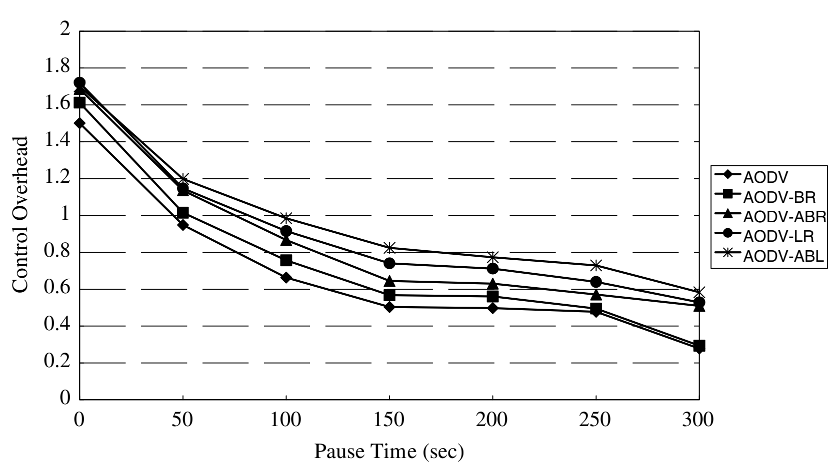


Fig. 12. Control overhead.

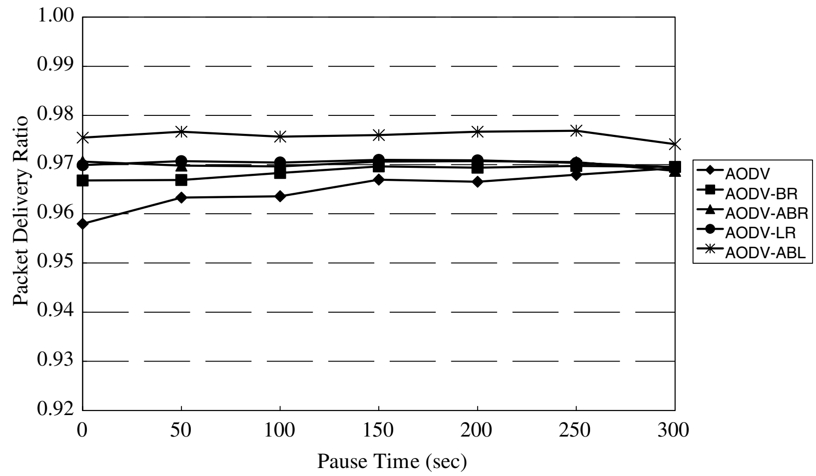


Fig. 13. Packet delivery ratio with traffic rate = 6 packets per second.

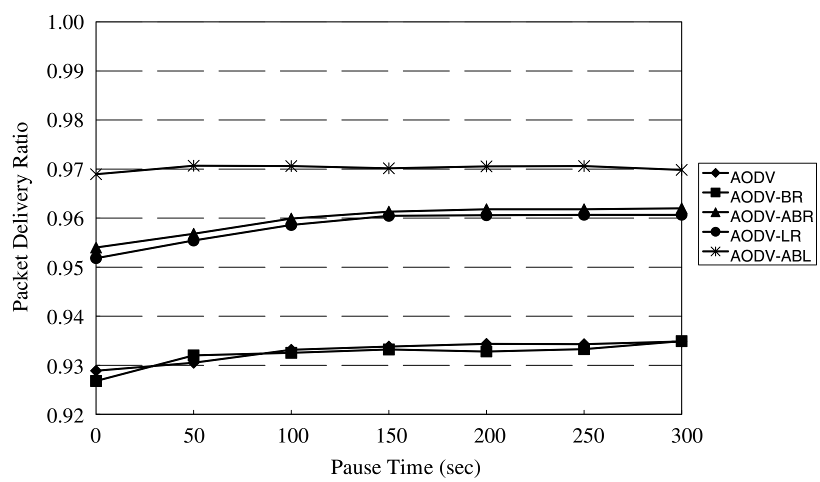


Fig. 14. Packet delivery ratio with traffic rate = 8 packets per second.

Figs. 13 and 14, we can claim that the throughput of all schemes degrades as the network traffic load increases. AODV-ABL, AODV–LR and AODV-ABR perform more effective route repairs when link failures occur. Therefore, their performances always are better than AODV and AODV-BR. When each session with a transmission rate of 6 packets per second, the packet delivery ratio of AODV-BR is higher than AODV. Once the data transmission rate is increased to 8 packets per second, in contrary, AODV and AODV-BR almost have the same performance. When the network traffic load is heavy, data packets being broadcasted through the alternate paths may collide with packets using primary route and degrade the overall throughput in AODV-BR. We also can notice that when the data transmission rate is increased to 8 packets per second, AODV-ABL still has the best performance and AODV-ABR becomes slightly better than AODV–LR.

As more nodes participating into a wireless network, the traffic loads will become heavier. The probability of packet collisions will also increase, and result in the degradation in overall performance. Such an inherent characteristic poses a great challenge to all kinds of approaches. In our simulation, we examine the system performance under heavy loads by doubling the traffic to 20 sessions with transmission rate at 4 packets per second. Fig. 15 reports the result of the scenario when traffic load was doubled. Comparing Fig. 9 (the packet delivery ratio t with 10 sessions) and Fig. 15, we can see that the effectiveness of all schemes decreased because of the increment in packet collisions when there are more data sessions. AODV-BR performs worse than AODV when we double the number of data sessions from 10 to 20. It is because data sent through alternate paths may collide with data transmitted via the main route as explained before (Fig. 6). The AODV-ABL (the combination of AODV-ABR and AODV–LR) outperforms the others. The AODV–LR and AODV-ABR have comparable performance and both are better than AODV and AODV-BR.

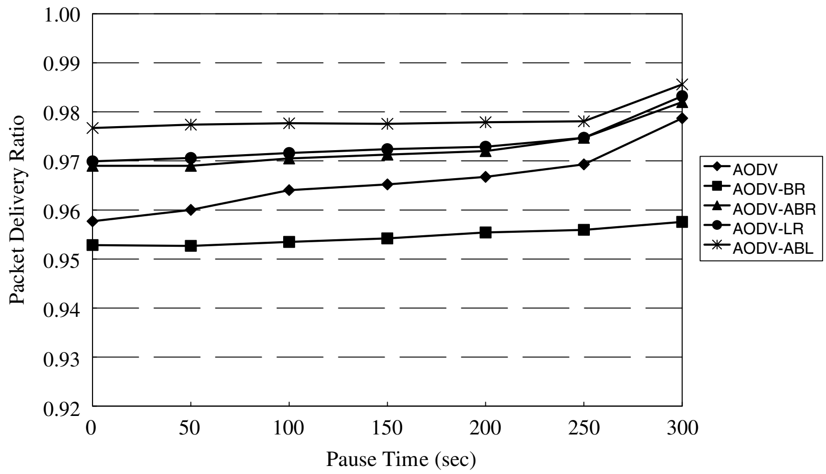


Fig. 15. Packet delivery ratio with traffic session = 20 pairs.

5. Conclusion

In this paper, we present a scheme called AODV-ABR (Adaptive Backup Route) which adapts to network topology variations. We also propose a new protocol named AODV-ABL which is the combination of AODV-ABR and local repair. Finally, the comparison of efficiency is made among AODV, AODV-BR, AODV-LR, AODV-ABR and AODV-ABL using the GloMoSim simulator. Simulation results show that AODV-ABL has the highest throughput, followed by AODV-LR or AODV-ABR and then AODV or AODV-BR. AODV-LR is more suitable for high loads. AODV-BR performs better in light loads and decreases in heavy traffic situation because of the increase in packet collisions when there are more and more traffic. AODV-BR in heavy traffics even performs worse than original AODV. Because AODV and AODV-BR do not require repairing the route when link failures occur, they both have smaller control overhead.

AODV-ABR utilizes the alternative routes of AODV-BR and the concept of AODV–LR. It can repair the failing route by only inquiring the immediate neighbor nodes that have alternate routes. Simulation results indicate that AODV-ABR is not only adaptive to the variations of network topology, but also has smaller control overhead than AODV–LR. It also can solve the collision and congestion problems of packets in AODV-BR by choosing a backup route among many backup routes. AODV-ABL which combines both advantages of AODV-ABR and AODV–LR would provide more stability for connections and retain highest performance under a high node mobility ad-hoc network.

The Quality of Service (QoS) is one of the most important issues for the modern networks. An ad-hoc network is a distributed environment. Prioritized QoS will be more suitable in such a distributed ad-hoc network. It is possible that different values of inter-frame spaces (IFS's) and contention windows (CW's) can be assigned to different traffics to meet their QoS requirements. When a link breaks down, an alternate route can be chosen according to the QoS requirements. In the future, we will improve the proposed schemes by taking the QoS issues into account.

Appendix A

Algorithm 1. Procedure for Packet Overhearing in AODV-ABR. Procedure for packet overhearing{

```
If (the type of received packet is a control packet) {
   If (the received packet is a RREP message) {
      If (There is no route to the destination in its alternate route table) {
         Create a new entry in its alternate route table;
         Record the IP of the neighbor as the next hop to the destination in the new entry;
         Increment the hop count field by one to account for the new hop through the previous node and record the new hop count in the new entry;
      }
      Else If (The destination sequence number of the received RREP is greater than the one recorded in the alternate route table || the hop count field of the received RREP with the same destination sequence number is smaller than the one in the alternate route table) {

      Update the destination sequence number;
      Update the hop count;
      Refresh the timeout value as the current time plus the value of ACTIVE_ROUTE_TIMEOUT [14];
   }
}

}Else if (Packet type is a data packet) {
```

If (The packet is transmitted by the next hop to the destination) {
If (There is no route to the destination in its alternate route table) {
Create a new entry in its alternate route table;
Record the IP of the neighbor as the next hop to the destination in the new entry;
Increment the hop count field by one to account for the new hop through the previous node and record the new hop count in the new entry;
}
Else If (The hop count of the received packet is smaller than the one recorded in its alternate route table) {
Update the hop count;
Refresh the timeout value as the current time plus the value of ACTIVE_ROUTE_TIMEOUT [14];
}
}
Else
Ignore the packet;
}

}

Algorithm 2. Procedure for Handling Link Break in AODV-ABR. Procedure for link-break handling{

Broadcast BRRQ to neighbors with TTL=1;
Wait for receiving BRRP packets;
If (BRRP packet received before timeout) {
Compare the hop count fields of all received BRRP packets;
Choose the BRRP with the smallest hop count;
Update the next-hop field in the routing table with the neighbor which transmitted the BRRP with the smallest hop count;
Update the hop count field in the routing table with the smallest hop count;
Relay data packets to the next hop;
}
Else
Send RERR back to the source;
}

Algorithm 3. Procedure for Receiving BRRQ in AODV-ABR. Procedure for receiving BRRQ{

If (There exists an entry to the destination in its alternate route table)
If (BRRQ packet is not received from the next hop to the destination) {
Reply BRRP packet to the initiator of BRRQ;
Copy the routing information from the alternate route table to the routing table;
}
}

Algorithm 4. Procedure for Handling Link Break in AODV-ABL. Procedure for link-break handling in AODV-ABL{

If (The destination is not farther than MAX_REPAIR_TTL hops away)
Start local repair;
Else {
Broadcast BRRQ to neighbors with TTL=1;
Wait for receiving BRRP packet;
If (BRRP packet received before timeout) {
Compare the hop count fields of all received BRRP packets;
Choose the BRRP with the smallest hop count;
Update the next-hop field in the routing table with the neighbor which transmitted the BRRP with the smallest hop count;
Update the hop count field in the routing table with the smallest hop count;
Relay data packets to the next hop;
}
Else

Send RERR back to the source;
}

}

References

[1] S.J. Lee, E. Royer, C.E. Perkins, Scalability study of the ad hoc on-demand distance vector routing protocol, International Journal of Network Management. 13 (2) (2003) 97–114.

[2] S. Corson, J. Macker, Mobile ad hoc networking (MANET): routing protocol performance issues and evaluation considerations, RFC. 2501 (1999).

[3] Internet Engineering Task Force (IETF) Mobile Ad Hoc Networks (MANET) Working Group Charter, Chaired by Joseph Macker and M. Scott Corson, http://www.ietf.org/html.charters/manet-charter.html.

[4] D.B. Johnson, D.A. Maltz, Dynamic source routing in ad hoc wireless networks, in: Mobile Computing, Kluwer Academic Publishers, 1996, pp. 153–181.

[5] J. Jubin, J.D. Tornow, The DARPA packet radio network protocols, Proceedings of the IEEE 75 (1) (1987) 21–32.

[6] S. Kim, W. Noh, S. An, Multi-path ad hoc routing considering path redundancy, Computers and Communications (ISCC'03) (2003) 45–50.

[7] S.J. Lee, M. Gerla, Split multi-path routing with maximally disjoint paths in ad hoc networks, Proceedings of IEEE ICC'01 (2001).

[8] S.J. Lee, M. Gerla, AODV-BR: Backup routing in Ad Hoc networks, Proceedings of IEEE WCNC 2000. Chicago, IL, (2000).

[9] M. Marina, S. Das, On-demand multi-path distance vector routing in ad hoc networks, Proceedings of IEEE International Conference on Network Protocols (ICNP'01) (2001).

[10] G.S. Malkin, M.E. Steenstrup, Distance-vector routing, in: M.E. Steenstrup (Ed.), Routing in Communications Networks, Prentice Hall, 1995, pp. 83–98.

[11] J. Moy, Link-state routing, in: M.E. Steenstrup (Ed.), Routing in Communications Networks, Prentice Hall, 1995, pp. 135–157.

[12] A. Nasipuri, R. Castaneda, S.R. Das, Performance of multipath routing for on-demand protocols in mobile ad hoc networks, ACM/Baltzer Journal of Mobile Networks and Applications (MONET) 6 (4) (2001) 339–349.

[13] A. Nasipuri, S.R. Das, On-demand multi-path routing for mobile ad hoc networks, Proceedings of the eighth Annual IEEE International Conference on Computer Communications and Networks (ICCCN), Boston, MA, October 1999, pp. 64–70.

[14] C.E. Perkins, Royer, and S. Das, "Ad Hoc On-Demand Distance Vector (AODV) Routing," Internet Draft, draft-ietf-manet-aodv-13.txt, February 2003.
[15] C.E. Perkins, Ad Hoc Networking, Addison Wesley (2001).
[16] C.E. Perkins, E. Royer, Ad hoc on-demand distance vector routing, Proceedings of IEEE WMCSA (1999).
[17] C.E. Perkins, P. Bhagwat, Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers, Proceedings of the ACM SIGCOMM. (1994) 234–244.
[18] Qualnet Simulator: http://www.qualnet.com.
[19] E.M. Royer, C.-K. Toh, A review of current routing protocols for ad-hoc mobile networks, IEEE Personal Communications 6 (2) (1999) 46–55.
[20] X. Zeng, R. Bagrodia, M. Gerla, GloMoSim: a library for parallel simulation of large-scale wireless networks, Proceedings of PADS'98 (1998).
[21] R. Dube, C.D. Rais, K. Wang, S.K. Tripathi, Signal stability based adaptive routing (SSR alt SSA) for ad hoc mobile networks, IEEE Personal Communication (1997).
[22] C.W. Yu, L.-H. Yen, K.-M. Yu, Z.P. Lee, "An ad hoc routing protocol providing short backup routes," ICCS 2002. The eighth International Conference on Communication Systems, vol. 2, November 2002, pp. 1048–1052.
[23] Y.-H. Wang, C.-C. Chuang, C.-P. Hsu and C.M. Chung, "Ad hoc on-demand routing protocol setup with backup routes". Proceedings of ITRE 2003. International Conference on Information Technology: Research and Education, 2003, August 2003, pp. 137–141.
[24] S. Tang and B. Zhang, "A robust AODV protocol with local update," Proceedingsof APCC&MDMC 2004, The Joint Conference of the 10th Asia-Pacific Conference on Communications and the 5th International Symposium on Multi-Dimensional Mobile Communications, 2004, vol. 1, August 2004, pp. 418–422.
[25] C. Gui, P. Mohapatra, SHORT: self-healing and optimizing routing techniques for mobile ad hoc networks, Proceedings of MOBIHOC (2003) 279–290.
[26] S. Tang, B. Zhang, M. Watanabe, S. Tanaka, A link heterogeneity-aware on-demand routing (LHAOR) protocol utilizing local update and RSSI information, IEICE E88-B (9) (2005) 3588–3597.

W. K. Lai received a BS degree in Electrical Engineering from National Taiwan University in 1984 and a Ph.D. degree in Electrical Engineering from Purdue University in 1992. He is now a professor of Department of Computer Science and Engineering, National Sun Yat-Sen University. His research interests are in wireless networks and high-speed

S. Y. Hsiao received the M. S. degree from Department of Computer Science and Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan, in 2004. His main interest is in wireless networks.

Y.-C. Lin received the B.S. degree from the Department of Computer Science and Information Engineering at National Chiao Tung University, Hsinchu, Taiwan, in 1991, and the M.S. degree from the Department of Computer Science at University of Southern California, USA. He is a Ph.D student in the Department of Computer Science and Engineering at National Sun Yat-Sen University, Kaohsiung, Taiwan. He is also an instructor at Tajen University, Pingtung, Taiwan. His research interests include QoS and wireless network